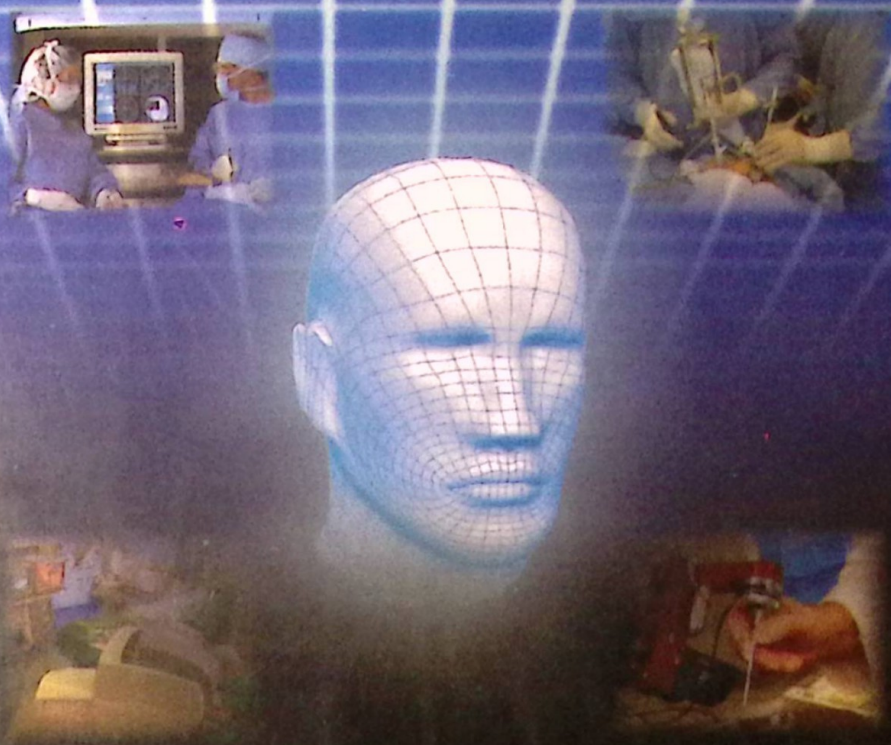
RESEARCH ON COMPUTING SCIENCE



e-Health: Application of Computing Science in Medicine and Health Care

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(Eds.)

EU-LAT

e-Health:
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Preface

This book presents a compilation of the papers presented at the EU-LAT Workshop on e-Health, held in Cuernavaca, Mexico on December 2003. EU-LAT (IST-2001-32792) is a FP5 EU funded initiative to bring together research groups from Europe and Latin-America and to create the conditions for them to build new research proposals. The quality and quantity of the work shows that e-Health is a very active and strong area of research in both sides of the Atlantic Ocean. It is clear that any improvement in the standards of Health services will be well received by society. We are very glad to show the ongoing work on this field and to serve as stepping stone for new ways of cooperation.

The papers have been organized in six topics: *Software Agents in Health Care, Information management and delivery, Mobile Computing and Ambient Intelligence, Data Analysis and Knowledge Discovery, Task Planning and Scheduling* and *Imaging, 3D Models and Surgery.*

In the first topic, *Software Agents in Health Care*, there are five papers that show the broad applications of Multi-Agent Systems in the Medical domain. The first paper (by *J. Nealon and A. Moreno*) is an overview of the use of agents in Health Care, while the rest present different interesting applications: personalization of services (*D. Isern et al.*), adaptation of user interfaces (*S. Greenwood, J. Nealon and P. Marshall*), building systems to support Care Communities (*M. D. Beer, W. Huang and R. Hill*) or assisting in the allocation of human organs and tissues (*J. Vázquez Salceda et al.*). The last two papers also propose agent frameworks for the design of such systems.

In the second topic, *Information management and delivery*, there are papers that focus on the uses of computer science to ease the information flow between patients and/or medical staff. The first paper (by *G. Madle et al.*) talks about the use of medical digital libraries on Internet in order to change knowledge and attitudes on professionals and patients. Then the second paper (by *P. Kostkova et al.*) focuses more on the role of digital libraries and the Communities of Practice in order to improve knowledge sharing. Finally, the third paper (by *P. López et al.*) presents an application to integrate the different kinds of information (text, images) related to the management of corneal tissues in a hospital.

The third topic, *Mobile Computing and Ambient Intelligence*, presents some research on the use of innovative technologies and concepts such as Mobile Computing, Embedded Systems or Ambient Intelligence in order to improve processes and tasks in a medical scenario. The first paper (by *M. Klann*) discusses possible uses of mobile computing to support people in collaborative settings. Then the second paper (by *U. Cortés et al.*) presents the role the integration of several technologies can play to build Ambient Intelligence scenarios to increase the patient autonomy. Finally, the third paper (by *M. Rodriguez et al.*) presents some research on the use of context-aware mobile devices in order to ease coordination and the access of professionals to the information.

In the fourth topic, *Data Analysis and Knowledge Discovery*, there are four papers showing the important role Artificial Intelligence methods can play in tasks such as the discovery of new information, diagnosis or classification. The first paper (by *J. González et al.*) applies decision trees and neural networks to analyze medical images and databases. The second paper (by *J.-W. Bang*) adapts Bayesian Networks to the classification of neural cell morphology. Then the third paper (by *J.*

Garcés Eisele et al.) applies solution algorithms for the Traveling Salesman Problem to the typing of DNA sequences in a laboratory. The fourth paper (by *H.-G. Acosta-Mesa et al.*) applies the NARMAX algorithm to study functional magnetic resonance images to extract a functional model of an area in the brain related with stereo-perception.

The fifth topic, *Task Planning and Scheduling*, collects papers showing the application of different methods to assist humans in the scheduling and planning of tasks, with positive impact in the daily medical practice. The first paper (by *M. Hannebauer and U. Geske*) presents on-going work on the application of Constrain Logic Programming (CLP) in a distributed setup where several CLP Solvers are coordinated to build a schedule for medical appointments. The second paper (by *A.I. Martinez-Garcia and R. Mendez-Olague*) discusses the adventages of using both static process modeling and dynamic process simulation to analyze complex processes, and they apply it to the analysis of an emergency room service in the Mexican public health sector. The third paper (by *M. Becker et al.*) analyzes the problem of task scheduling in a medical environment and proposes the introduction of the actors' preferences as part of the planning task and the use of software agents' negotiation to solve conflicts. The fourth paper (by *C. Urdiales et al.*) applies a navigation planning architecture to schedule the order of the tasks of the hospital member staff in order to work in an efficient way.

The sixth topic, *Imaging, 3D Models and Surgery*, groups those papers presenting applications of computer science to process images and interact within virtual or real 3D environments. The first paper (by *L. Joskowicz and R. H. Taylor*) is an overview of Computer Integrated Surgery systems, explaining the different technologies, elements and interfaces involved and presenting some examples. Then the second paper (by *J. Márquez Flores et al.*) presents a method for automatic extraction of anatomical models to create a craniofacial computerized atlas to be used for simulation and research on prostheses. The third paper (by *M. A. Padilla Castañeda and F. Arámbula Cosío*) presents a computer simulator to train the user in Prostate Surgery. The fourth paper (by *V.J.L. Mosso et al.*) presents the evolution in robotic laparoscopic assistants in the last eight years. The last paper (by *J. L. Mosso and A. Minor Martínez*) presents some of the experiences on the use of a hand-free navigation system in a laparoscopy robot.

To end this preface we want to thank the EU, ITESM and IPN for its institutional support, to the authors for the interest they showed in our workshop, and to all the people involved in organizational tasks before and during the workshop days.

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Agent-Based Applications in Health Care

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Abstract. In this paper we introduce the main issues related to the deployment of agent-based systems in health care. First, we comment on the characteristics of health care problems and we argue that multi-agent systems are a good choice to tackle problems with these features. This belief is supported with a number of exemplar applications of agent-based systems in medical domains. We also discuss several lines of research that have to be covered before multi-agent systems can be successfully deployed in real health care settings. We conclude that multi-agent systems do have an increasingly important role to play in health care domains, because they significantly enhance our ability to model, design and build complex, distributed health care software systems.

1 Introduction

Health care at all levels - local, regional, national and international - is a vast open environment characterized by shared and distributed decision making and management of care, requiring the communication of complex and diverse forms of information between a variety of clinical and other settings, as well as the coordination between groups of health care professionals with very different skills and roles. It is the aim of health care software systems to operate effectively in this environment, in order to meet the information needs of patients and health care providers. Practitioners in health care environments, in particular, require that the information is both timely and error-free, such that recommendations or decisions offered by the software systems are secure and trustworthy [1].

There is a growing interest in the application of agent-based techniques [2], [3] to problems in the medical domain1. In this paper we explain which are the characteristics of the problems in this area, and we argue that multi-agent systems are indeed an interesting tool to solve them, since the usual properties of intelligent agents match quite precisely with our needs in this field (basically with the requirement of having autonomous intelligent proactive collaborative entities in a distributed environment). This volume is another empirical confirmation of this claim, since it presents an extensive list of agent-based systems that are being

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developed across Europe to solve a wide range of problems in health care (from the management of organ and tissue transplants to the provision of personalised access to medical information to diabetic patients). All these systems are being developed by the members of the AgentCities.NET Working Group on Health Care Applications [7].

Despite the adequacy of multi-agent systems in the building of health care systems, it must be stressed that there are still many research topics that have to be thoroughly studied before multi-agent systems may be successfully deployed in real health care settings. Section 3 offers a summary of the main current research and development topics relevant to the application of agents to health care.

2 Agent-Based Systems in Health Care

2.1 Agents and Multi-Agent Systems

An agent is a software entity that applies Artificial Intelligence techniques to choose the best set of actions to perform in order to reach a goal specified by the user. It is normally assumed that they have the following properties:

- They can react timely and flexibly to the dynamic and unexpected changes in their environment.
- They have an autonomous and independent behaviour, which is not controlled by any external entity.
- They can take the initiative and perform proactively actions that may help them to reach their goals.
- They can communicate with users or other agents. Thus, they can exchange information, engage in complex negotiations, and coordinate their activities to cooperate in the joint resolution of a problem.
- Agents usually have reasoning, planning and learning capabilities that allow them to display an intelligent behaviour.

A multi-agent system [2], [3] might be defined as a collection of autonomous agents that communicate between themselves to coordinate their activities in order to be able to solve collectively a problem that could not be tackled by any agent individually. In recent years it has been argued that multi-agent systems may be considered as the latest software engineering paradigm [8], [9]. This kind of system may be used in domains with the following features:

- The knowledge required to solve the problem is spatially distributed in different locations.
- Several entities, while keeping their autonomous behaviour, have to join their problem-solving abilities to be able to solve a complex problem.
- The problems in the domain may be decomposed in different sub-problems, even if they have some kind of inter-dependencies.

2.2 Characteristics of Problems in the Health Care Domain

It is interesting to note that many problems that appear in health care share a number of similarities. Noting these similarities is a good first step towards finding a framework that may be used to approach most of these problems. Among the most important characteristics of problems in the medical field we can cite the following:

- It is very usual that the knowledge required to solve a problem is spatially distributed in different locations. For instance, the problem of patient scheduling [10, 11, 12] consists in scheduling the different tasks to be performed on a hospitalised patient (e.g. a number of different analysis and tests). Normally, each unit of the hospital keeps its own information about the patients hospitalised in that unit and about the schedule of the activities with the unit's equipment. There are units that provide services to all the other units of the hospital, such as X-rays or blood tests. It is not trivial to coordinate the schedule of different tests to be performed in different units, especially if, apart from the temporal restrictions derived from the separate location of different units, there are also medical restrictions among the tests (e.g. one test has to be performed at least two hours after another test).
- The solution of a problem involves the coordination of the effort of different individuals with different skills and functions, usually without the supervision of a single centralised coordinator. The provision of health care typically involves a number of individuals - inpatients, outpatients, physicians, nurses, carers, social workers, managers, receptionists, etc. - located in many different places. Patients could be at home, at work, in hospital, or on vacation, while the health care providers are often at a number of institutions or locations within institutions, providing services such as diagnosis, treatment, surgery, laboratory testing, radiography, and so on. All these people must coordinate their activities to provide the best possible treatment to the patient.
- Health care problems are quite complex, and finding standard software engineering solutions for them is not straightforward. For instance, coordinating the process of organ transplant in a country is not an easy task [13]. When a new organ is available, it is necessary to find very quickly the most appropriate receptor of the organ, which may be located in a medical centre hundreds of miles away from the donor's location. Furthermore, as commented above, each hospital keeps the data of the patients of that hospital who are in the waiting list for a certain type of organ. It would be quite difficult to design and implement a centralised complex system (e.g. a standard decision aid expert system) to solve this coordination problem.
- In the last few years there has been a shift in health care practice towards health care promotion, shared patient-provider decision-making and managed care, creating an increased demand for information and online services [14, 15]. The shared decisions and actions of all concerned need to be coordinated to make sure that the care is efficient and effective. To facilitate

this decision-making task, and to ensure the communication and coordination processes run smoothly, software systems are needed that will reduce errors in diagnosis and treatment, deliver health care to remote locations, improve medical training and education, and make health care information more accessible to patients, their families and carers, alike. To meet these needs the software systems must be proactive in anticipating the information and knowledge needs of users and deliver it in a timely manner, support synchronous and asynchronous communication, and facilitate collaborative decision making between the various individuals involved in the process of managing and delivering health care services.

- There is a great amount of medical knowledge available on the Internet. It is necessary to provide ways of accessing the most relevant information as easily, flexibly and timely as possible. This access to medical information is necessary both for medical practitioners and for patients. In the former case, they have to be aware of all the new medicines, techniques and treatments appearing in their field of expertise; however, most practitioners lack the time to search for all this information and filter the one they need exactly. In the latter, citizens demand a more active role in the management of their care, and they want to find relevant information as easily as possible (but they usually lack the skills to search for the most adequate knowledge relevant to their specific personal needs). In both cases it is important to receive appropriate information from useful and reliable sources in a proactive way, without having to devote time and effort to look for, analyse, evaluate and filter it.

2.3 Adequacy of Agent-Based Systems to Health Care Problems

We would like to argue in this paper that multi-agent systems offer an appropriate tool to tackle this kind of problems. Some reasons to support this claim are the following:

- The components of a multi-agent system may be running in different machines, located in many different places. Each of the agents may keep part of the knowledge required to solve the problem, such as patient records held in different departments within a hospital or in several hospitals, clinics and surgeries, in an insurance company, or in government organisations. Therefore, multi-agent systems offer a natural way of attacking inherently distributed problems.
- One of the main properties of an intelligent agent is sociability. Agents are able to communicate between themselves, using some kind of agent communication language, in order to exchange any kind of information. In that way they can engage in complex dialogues, in which they can negotiate, coordinate their actions and collaborate in the solution of a problem (e.g. different units of a hospital may collaborate in the process of patient scheduling [10, 11, 12].

- When a problem is too complex to be solved in a single system, it is usual to decompose it in subproblems (which will probably not be totally independent of each other). In multi-agent systems there are techniques of distributed problem solving [16], in which a group of agents may dynamically discuss how to partition a problem, how to distribute the different subtasks to be solved among them, how to exchange information to solve possible dependences between partial solutions, and how to combine the partial results into the solution of the original problem. Thus, multi-agent systems can handle the complexity of solutions through decomposition, modelling and organising the interrelationships between components.
- Agents can also be used to provide information to doctors and patients. There are information agents (also called Internet agents, [17], that are specialised in retrieving information from different sources, analysing the obtained data, selecting the information in which a user is especially interested, filtering redundant or irrelevant information, and presenting it to the user with an interface adapted to the user's preferences.
- Another important property of agents is their proactivity; their ability to perform tasks that may be beneficial for the user, even if he/she has not explicitly demanded those tasks to be executed. Using this property they may find relevant information and show it to the user before he/she has to request it. For instance, if it knows that the user has had heart problems in the past and might need this information urgently, a personal agent that also knows that the user is about to travel abroad could look for information about the medical centres in the towns to be visited that have a cardiology department.
- The basic characteristic of an intelligent agent is its autonomy. Each agent takes its own decisions, based on its internal state and the information that it receives from the environment. Therefore, agents offer an ideal paradigm to implement systems in which each component models the behaviour of a separate entity, that wants to keep its autonomy and independence from the rest of the system (e.g. each unit of the hospital may keep its private data, or each hospital may use a different policy to rank the patients that are waiting for an organ transplant).

Thus, we think that the basic properties of intelligent agents (autonomy, proactivity, social ability) and the features of multi-agent systems (management of distributed information, communication and coordination between separate autonomous entities) suggest that they offer a good option to consider when trying to solve problems in health care domains.

2.4 Fields of Application within Health Care

Intelligent agents have already been proposed to deal with many different kinds of problems in the health care domain (see [4], [5], [6], [7] and the rest of the chapters of this volume). Just to give a short list of examples, some of the fields in which they are already being applied are the following:

- Patient scheduling: in patient appointment scheduling, where medical procedures have become more complex and their tests and treatments more interrelated, manual and traditional software solutions have been shown to be inadequate while a multi-agent solution gave significantly improved results [10, 11, 12]. The complexities of medical appointment scheduling have been successfully formalised and implemented in an agent framework [18].
- Organ and tissue transplant management: the agent-based coordination of tissue or organ transplants across a hospital [19, 20, 21] could provide significant improvements in the time required to pull together the resources required for a transplant operation. This approach could also be feasible at a regional level where each hospital has a list of waiting patients, and when an organ is available somewhere in the region, the hospital transplant coordinators must get in touch and quickly find the most appropriate recipient [13].
- Community care: coordinating all the activities that have to be performed in order to provide an efficient health care to the citizens of a community (especially older or disabled citizens). Agents can provide remote care monitoring and information for such groups as the elderly and chronically ill. There is an elderly care management system [22] in which one agent is associated with each elderly person that is responsible for receiving medical data, giving reminders to the person, and alerting the medical centre if something is wrong.
- Information access: the deluge of medical information available on the Internet has led to the development of information agents to collect and organise this information, such as the Multi-Agent Retrieval Vagabond on Information Networks (MARVIN) [23], developed by the Health On the Net Foundation and the Swiss Institute of Bioinformatics, or a multi-agent system that helps to manage the UK National Electronic Library for Communicable Diseases [24]. An information agent, based on a user profile, has proactively performed the role of locating, assessing, retrieving, filtering and presenting information from many distributed sources on a periodic basis [25]. An intelligent user interface to adapt to a clinicians requirements, specialism and the characteristics of diabetic patients whose records are being accessed uses a multi-agent framework to coordinate these possibly conflicting requirements [26]. It has also been implemented a multi-agent system that provides mobile users with information about the medical centres or the doctors available in a particular town, and that lets the user access his/her medical record or book a visit to be examined by a doctor [27].
- Decision support systems: A distributed decision support system based on the multi-agent paradigm can monitor the status of a hospitalised patient and help to diagnose the state of the patient [28], or support co-operative medical decision- making [29], [30].
- Training: agents can help to improve medical training and education in distance- learning tutoring systems [31].
- Internal hospital tasks: Patient information retrieval and workflow management using agent communication techniques and medical ontologies is being

applied to the management of patients suffering from stroke [32, 33]. A cooperative multi- agent framework can support the heterogeneous transaction workflow process among the people involved in patient care management [34]. Multi-agent systems have also been suggested for monitoring the application of medical protocols [35], or controlling the usage of restricted use antibiotics [36].

- Senior citizen care: a group of special interest for the application of agent-based systems are the senior and the disabled citizens, to whom this technology could be useful to help to increase their ability to lead an independent life. Those agent systems have to be devised to provide aid in carrying out activities of daily living, and health care maintenance. In addition, they will provide links to the outside world, including entertainment and information, and will facilitate communication with family and the environment. Their functions may include standardised behavioural assessments useful in medical monitoring. These kinds of tools may be used to facilitate the health care and social interaction of senior citizens person, and may delay their institutionalisation by prolonging the period of relative independence [37]. A European IST project, TeleCARE, aims to design and develop a configurable agent-based framework for virtual communities focused on supporting assistance to elderly people employing tele-supervision and tele- assistance [38].

3 Research and Development Challenges

There are several issues that must be addressed if multi-agent systems are to be successfully deployed in real world health care applications. A discussion of the most significant of these follows.

3.1 Communication standards

Health care systems are complex, diverse and dispersed. Consequently, the development, dissemination and utilization of common communication standards, vocabularies and ontologies are and will be central to the development of multi-agent systems in health care. In the main, communication standards (sometimes called specifications or protocols) already exist. For some time the EU and US standardization bodies for health care information and communications technology have been overseeing the development of communications standards. The EUs CEN/TC 251 [39] aim is to achieve compatibility and interoperability between independent systems, to support clinical and administrative procedures, technical methods to support interoperable systems as well as requirements regarding safety, security and quality. The two most well known US standardization bodies, the American Society for Testing and Materials Committee on Healthcare Informatics (ASTM E31) [40] and Health Level Seven (HL7) [41], are involved in similar work. ASTM E31 is developing standards related to the

architecture, content, storage, security, confidentiality, functionality, and communication of information. HL7 is mainly concerned with protocol specifications for application level communications among health data acquisition, processing, and handling systems. Its scope is wide in that it attempts meet the communication requirements of entire health care organisations, while most other efforts focus on the requirements of a particular department, whereas most standards organisations produce standards for a particular healthcare domain such as pharmacy, medical devices, imaging or insurance (claims processing) transactions. HL7s domain is clinical and administrative data. "Level Seven" refers to the highest level of the International Standards Organisation's communications model for Open Systems Interconnection. HL7 defines the data to be exchanged, the timing of the interchange, and the communication of certain errors to the application. The seventh level supports such functions as security checks, participant identification, availability checks, exchange mechanism negotiations and, most importantly, data exchange structuring.

3.2 Ontologies

Ontologies are being developed specifically for health care applications. The best known examples are GALEN [42], the Unified Medical Language System (UMLS) [43], Systematized Nomenclature of Human and Veterinary Medicine (SNOMED) [44]. The aim of GALEN is to produce a computer-based multilingual coding system for medicine. The GALEN Programme is developing a clinical terminology - the GALEN Common Reference Model for medical concepts. The medical concepts represented can be represented using a scheme that can both be manipulated by computers and accessible to health care professionals. The representation scheme that is being used to build the GALEN Common Reference Model is known as GRAIL - the GALEN Representation And Integration Language. It is intended for use by clinical application builders, both when developing clinical applications, and as a run- time resource when those applications are in service. The U.S. National Library of Medicine (NLM)'s UMLS project develops and distributes multi-purpose, electronic "Knowledge Sources" and associated lexical programs, for use in the development of systems concerned with patient records, digital libraries, Web and bibliographic retrieval, natural language processing, and decision support. The UMLS project is a long-term NLM research and development effort designed to facilitate the retrieval and integration of information from multiple machine-readable biomedical information sources. Major barriers to effective retrieval and integration of information from these sources include the variety of vocabularies and classifications used in different sources and by different users and the sheer number and wide distribution of potentially relevant information sources. These barriers deter health care professionals and researchers from using available machine-readable information and also hamper the development of effective search interfaces that might assist these users. The UMLS is a relational database connecting by concept over 60 vocabularies, thesauri, medical problem lists, etc. Its purpose is to make it easy

for health professionals, medical librarians, and researchers to retrieve and integrate information from different machine-readable sources as computer-based patient records, databanks, bibliographic and full text databases, and expert systems. SNOMED's design is based on the premise that a detailed and specific nomenclature is essential to accurately reflect, in computer readable format, the complexity and diversity of information found in a patient record. SNOMED is designed for applications such as telemedicine, population-based outcomes analysis, cost-effectiveness studies, practice guidelines and the integration of electronic medical record information into a single data structure. Nevertheless, the story on ontologies is not as clear as that on communication standards. Although bioinformatics and health care informatics are fields that have active communities developing ontologies, as we have seen with GALEN, UMLS and SNOMED, their use has lagged behind their potential, despite the huge drive by health care professionals to bring health care information into clinical workstations and onto the Internet. Why is this? GALEN provides a common terminology that is currently of limited scope, while UMLS lacks a strong organisational structure, and SNOMED provides only diagnosis nomenclature and codification. Those who are building health care applications are using ontologies that have been or are being developed to meet specific needs, each with its own representation of the world, suitable to the purpose it has been developed for. There is as yet no common ontology. The experience of system developers [45] strongly suggests that the development of a single or a small number of ontologies for the health care domains is non-productive since no single domain requires such an ontology, and the overlap between ontologies is often minimal. Perhaps, this challenge will eventually be taken up in the mould of CYC [46], but that is not likely in the immediate future. Alternatively, machine learning techniques for the automatic construction of ontologies are being developed [47, 48, 49, 50]. In the meantime, researchers working in related areas are sharing and extending existing ontologies.

3.3 Security and privacy issues

Security is concerned with the protection of information from unauthorised access while stored and communicated, and privacy protection with the avoidance of unnecessary identification. The increasing dependence on information and communication technologies in health care organisations in order to collect, transmit, store, and assess data has brought the dual issues of security and privacy to the fore. It is accepted that medical data, such as genome information, medical records and other personal information must be treated with the greatest respect with regard to privacy and privacy [51]. The European Union has been enforcing the protection of medical data of individuals since 1995 [52], and in many countries, such as in Spain, these recommendations are among the most modern state laws that address the specific protection of this kind of data. Recently a US law that regulates the treatment of medical data was passed [53]. This law establishes which rules must be followed by the software business in this field, and the fines that will be applied to those that do not comply with the

regulations. This text, however, does not force any specific standard for storing or transmitting data. The usual properties of confidentiality, integrity and non-repudiation should be guaranteed in any agent-based health-care system. The use of cryptographic methods is also important to protect the access to data while it is being transmitted between agents (some issues related to secure communication are discussed in [54]. Frameworks that help to construct multi-agent systems are beginning to address security issues. For instance, an authentication mechanism is being added to Jade [55, 56, 57]. A user will give a username and a password to enter the system; then the system will provide an identity certificate that may be used by the agents associated with that user. This certificate will include aspects such as the identities of the user and of the emitting entity, identification of the algorithms used to protect the certificate, and its validity period. It is also suggested in [58] that agents should also have authorization certificates that allow them controlled access to particular resources; these permissions could be obtained from the user at creation time or by delegation of other agents of the system. In summary, it is obvious that the research on secure access to data, such as authentication of users, delivery and use of certificates, cryptographic methods, or security in wireless communications, will be fundamental to ensure that agents may safely deal with medical data and only authorised users may access or update this kind of information.

3.4 Safety critical issues

Agent-based systems are increasingly being used to support decision making in health care, a domain intrinsically uncertain and hazardous. Clinicians are well aware of these risks, and a recurring theme in physicians' criticism of health care computer systems is one of doubts concerning reliability, and the associated acceptance criteria for reliability which are related to risk and safety considerations. Consequently, everyone working in this area should be aware that very small system errors or misunderstanding in the specification of systems can lead to catastrophic consequences [1]. There exist powerful theoretical models of agency [59, 60, 61], and techniques for the specification and formalisation of agent-based systems, and techniques to analyse and manipulate such specifications, utilising symbolic information to determine appropriate behaviour, are beginning to emerge, based on well-established research from AI [62, 63, 64]. For example, tableaux for multi-modal belief or knowledge logics [65], tableaux for multi-modal belief or knowledge logics with linear-time temporal logic [66], tableaux for belief-desire-intention logics with either linear or branching-time temporal logics [59], and resolution for knowledge logics with linear-time temporal logics [67].

3.5 Legal issues

The distributed aspect of multi-agent systems and the lack of electronic borders facilitate the construction of multi-agent systems in which agents are representing organisations and individuals from different countries. If a multi-agent system

is used to enhance the provision of health care to citizens of a wide area, such as coordinating the management of organ transplants in different countries, one of the most difficult issues to consider is the fact that agents should conform to the local, national and international regulations in their area. The use of deontic logic would be appropriate to formalise and reason about the permissions and obligations of each agent in a system. A very promising research direction in this area is the definition of electronic institutions (see e.g. [68], [69]. An electronic institution includes a performative structure (a graph of scenes, where agent-agent interactions take place), a dialogical framework (which comprises an ontology, a set of illocutions and protocols to use them through conversation graphs) and a set of norms, which determine obligations that an agent may acquire through its actions. An e-institution prescribes the actions an agent may take and where, and imposes limits on the questions and answers which form the conversation between agents. Thus, an institution simplifies the task of preparing an agent for a negotiation task, since the range of the discourse is predefined in the dialogical framework and the rules which must be adhered to for the negotiation to complete satisfactorily are laid down in the performative structure.

3.6 Social acceptance

Citizens continuously demand more control over their medical information. They would like to have permanent access to it, such as via the Internet and digital TV, but they want to make sure that only those authorised to do so can have access to it, and only when appropriate. Individuals need to be confident that this information will not be disclosed, either on purpose or inadvertently, to third parties, such as government, employers, insurance companies, marketing companies, pharmaceutical companies, who may then use it for their own purposes. This feeling implies, aside from the security issues mentioned above, the need to build a relation of trust between citizens and agents that provide the access to sensitive information [54]. We consider that the AgentCities initiative may be a very important step in this direction; as it will promote the construction of platforms all around the world that will provide agent-based services, the human users of these systems will start to use them and gain confidence in the relegation of tasks to autonomous entities. Work on trust [70] provides an interesting analysis of relevant issues in this area.

3.7 Professional acceptance

In general, it has been observed that health care professionals are quite reluctant to accept and use new technologies. In the first place, they usually have a very busy schedule, so they lack the time to be aware of the latest advances in technologies and how they could be used to reduce their workload. They refuse to use new tools if they are not integrated smoothly into their daily workflow. They also often mention the lack of time and personnel to convert all the required medical data into an electronic format, so that it can be easily accessed and

managed - medical records are usually hand written and distributed in different departments of a medical centre. Some doctors also mention the hype built around Artificial Intelligence and, especially, expert systems, twenty years ago, which did not live up to their expectations, and they may reasonably argue that the intelligent autonomous agent paradigm, so fashionable today, may also fail to deliver real world results. Security in the access to data is also a common concern for health care professionals. Agent systems have the potential to introduce many innovations in the way in which computer systems respond to clinicians. For example, they could identify the user by behaviour or even voice, adapt the user interface to their way of working, and document diagnoses and therapies.

3.8 General issues

There are also many technical problems associated with the development of multi- agent systems in any domain (not especially related to health care). These include user expectations and acceptance, the lack of universally accepted standard agent communication languages, protocols and architectures (although FIPA seems to be clearly leading these efforts and their suggestions are starting to become a de facto standard), how to describe the services offered by agents, how to discover the presence of agents that provide a given service, how to guarantee the identity of an agent that is making a certain request, security, safety and trust issues, how to implement agents that offer wireless access to services (e.g. from mobile phones or PDAs, which will probably be the key towards a massive use of agent technology in the near future), how to handle properly the interactions between software agents and humans, and integration with pre-existing health-care systems.

4 Conclusion

In this position paper we want to argue that multi-agent systems have a set of characteristics that make them appropriate to be used to improve the provision of health care to citizens:

- They may be integrated with existing applications, for example agents may access a database to obtain the information about the patients of a certain hospital [13].
- The agents in a multi-agent system may be running in different locations, for example there may be an agent associated to each department of a medical centre [27], or an agent associated to each person that is included in a health care program in a certain community [22].
- The standards provided by FIPA [71] and the FIPA-compliant frameworks of multi-agent system development are reaching a level of maturity that make it feasible to think in world wide applications that coordinate the activities of health care in different countries, for example coordinating the management of organ transplant with a whole European perspective, following ideas similar to the ones suggested in [13].

- The autonomy of each agent in a multi-agent system permits to maintain the independent views of each modelled actor, for example each agency involved in the provision of health care to a community, such as social workers, health care professionals or emergency services may have different private policies that determine their relationship with other agents and their individual decisions [22].
- Information agents may help both citizens and health care professionals to obtain up-to-date and relevant health care information from Internet, for example see [23].
- Agents may help to address the growing demand of patient-centred management of medical data, for example it is feasible to think about the possibility of having personal agents which are able to get in touch with agents at a medical centre to receive information about their medical record or to make an appointment to be visited by a doctor [27].

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Personalisation of Medical Services

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Abstract. In this paper we describe an application called HECASE, which is an agent-based system that provides medical services to its users (the citizens or the visitors of a city). This multi-agent system contains agents that have information about the medical centres, departments and doctors of a region. All these agents coordinate their tasks to provide a set of services to the user of the system, who can search for medical centres satisfying a given set of requirements, as well as access his medical record, or make a booking to be visited by a particular kind of doctor. Special care has been paid to the implementation of mechanisms that guarantee the confidentiality in the access and transmission of medical data, and provide personalised information using a dynamically updated user profile.

1 Introduction

The new information technologies allow people to access eficiently a wide range of data and services. Our aim is to use these tools to solve daily problems to improve the citizens quality of life. We focus our research in the health care domain using multi-agent systems technology (MAS) [15], that offers an added value in front of classical approaches such as web-based applications [3]. A MAS has the following interesting properties:

- *Modularity:* the different services or functionalities may be distributed among diverse agents, depending on their complexity.
- *Efficiency:* agents may coordinate their activities to perform complex tasks, so that several parts of the same process may be solved concurrently by different agents.
- *Reliability:* any distributed process is more reliable than its centralised counterpart, because there does not exist a single point of failure that may cause the crash of the whole system.
- *Flexibility:* agents may be dynamically created or eliminated according to the needs of the application. Negotiation and knowledge exchange allow the optimisation of shared resources.

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- *Existence of a standard:* the FIPA (Foundation for Intelligent Physical Agents, [8]) is a non-profit foundation based on Geneve (Switzerland). Its main mission is to establish the rules that have to govern the design and implementation of a MAS in order to achieve interoperability among systems. Since 1997 it has been releasing specifications that have been slowly gaining acceptance and have turned into de facto standards in the agents community. Due to this fact, any of our agents is compatible with any other agent that follows the same specifications.
- *Existence of development tools:* JADE (Java Agent Development Environment, [13]) is a programming tool that contains a set of JAVA libraries that facilitate the development of FIPA-compliant MASs. Apart from providing low level agent management functionalities and graphical interfaces that ease development and debugging, it also provides an execution environment for agents. Recently, a JADE plug-in that provides certain security mechanisms, called JADE-S, has been released.

In this paper we describe the design and implementation of a MAS called HECASE that offers secure personalised health care services. The rest of the paper is organised as follows. First of all, in §2 we give a general overview of the HECASE system. Section §3 explains how the system adapts dynamically its behavior to the user's profile. In §4 we offer an overview about security issues. The paper finishes with a discussion of the work done and some future lines of research.

2 HECASE: Overview

HECASE is a MAS prototype that models the medical institutions of Catalonia [3]. The main design objectives are the following:

- To provide a decomposition of the problem that allows to model the real entities of the medical domain as agents, based on the structure of medical centres in Catalonia [3] (each centre has a set of departments, and each department has a set of doctors).
- To provide an ontology for the medical domain [10].
- To provide security measures that ensure the confidentiality and privacy of medical data such as Secure Socket Layer (SSL) for message ciphering and Public Key Infrastucture (PKI) and Hash functions for authenticating and user's access control [9].
- To make the developed agent services as reusable as possible by: (1) using standard languages - in this case FIPA-ACL ([7]) for agent language communication and Resource Description Framework (RDF, [4]) for content and representation of ontologies - and (2) providing detailed service models to describe the individual functioning and objective of each agent including descriptions of actions, protocols used and example messages [10].
- To implement mechanisms to allow the user to adapt his Personal Agent behavior based on his profile. This will be very useful to guide a negotiation or to make proposals according to the user's preferences (See §3).

- To provide ubiquitous access to the system from anywhere, anytime [10].

With these aims, we have implemented a MAS that offers the following features (more details in [10]):

- The user may request information about all the medical centres available in a particular geographical area.
- It is possible to book a visit to be examined by a doctor.
- As mandated by a Catalan law [2], the user has access to his medical record.
- It must be made sure that nobody can access the private medical information of the users of the system without proper authorisation.
- The user can manage his own timetable and a set of preferences in order to select the most appropriate proposal or sort a list of options in the booking negotiation protocol.
- The doctor can manage his working hours and patient's appointments. During an examination, he is able to access the patient's medical history and to update it with the result of the visit.

2.1 Architecture

The basic architecture of the MAS which has been developed in this work is shown in Fig. 1. This multi-agent system contains the following agents:

i) The user's personal agent (PA), that provides a graphical interface of the MAS to the user, allowing the access to the offered services (queries, bookings, agenda, preferences...).

ii) The broker agent (BA) is an agent that provides a gateway between personal agents and the rest of the agents in the system. It controls the access of users that are properly authenticated.

iii) The information of a medical centre is divided in three levels. For each medical centre there is one medical centre agent (MCA), several department agents (DEPs, one for each department of the centre) and many doctor agents (DAs, one for each doctor of each department). The MCA has the general information of the centre (e.g. its address and opening times). Each DEP has the knowledge of a certain department (e.g. all the information of the Ophthalmology department). Each DA maintains the schedule of a given doctor, and is aware of the doctor's visiting times. They also implement a graphical interface to the doctor that is used to manage the list of pending visits with patients, to introduce the results of a medical visit and to look up the patient's personal data.

iv) The database wrapper (DW) is the agent that controls the access to a database that contains the medical records of the users.

The agents are stored in several containers within a single platform [7]. The MCAs (with DEPs and DAs) and the DW are internal to the system and only the BA is accessible by external agents. The PAs are running in the user's machine in an external container. The internal agents could be deployed physically around several machines in a real setting, e.g. each MCA (with its hierarchy of associated agents) could be running in a separate machine.

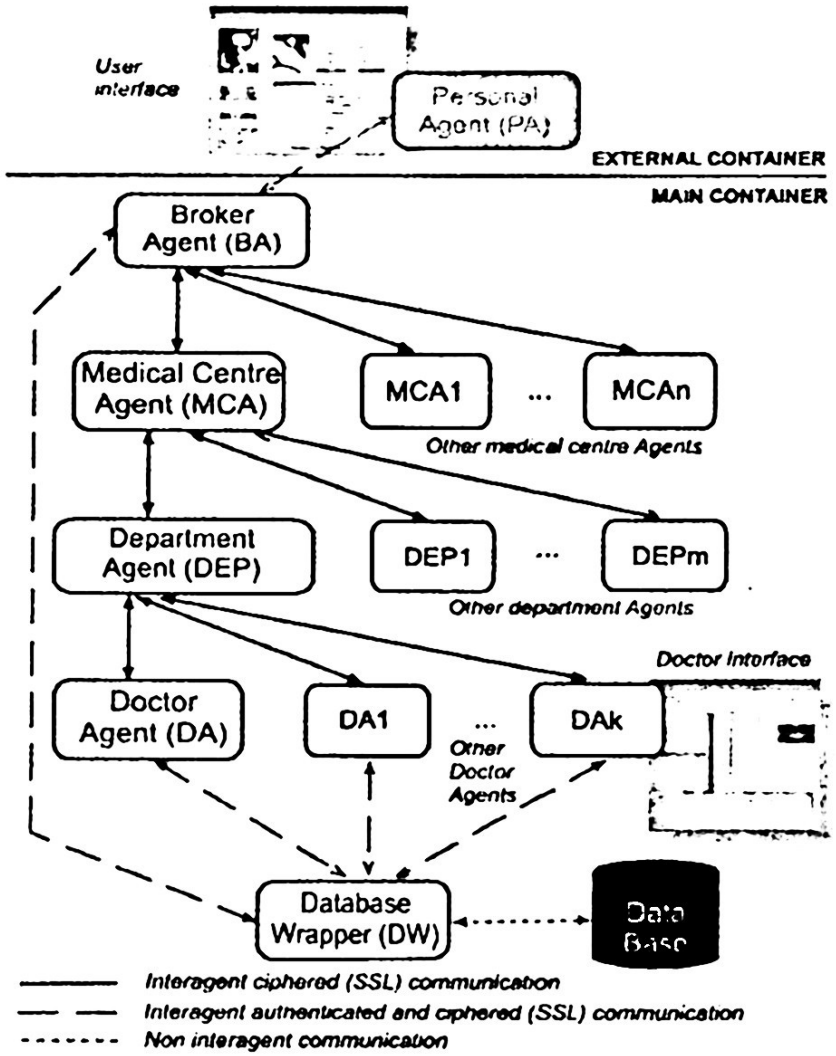

Fig. 1. Architecture of HECASE

3 Service personalisation

In order to provide more personalised services, each patient has his own profile which stores personal data (e.g. name, address, birth date, job), medical information (e.g. allergies, disabilities, medical antecedents), security elements (e.g. login, password), timetable (e.g. appointments, reminders) and preferences (e.g. ranking of doctors, medical centres and cities). The first three items are used to create the personal record that can be accessed by doctors or by the owner (after an authentication process, [9]). The timetable and the preferences are used to guide and personalise the booking negotiation process, as described in the following subsections.

3.1 Timetable plug-in

The *timetable plug-in* is a domain independent package for time management and scheduling visualisation. The list of features that this plug-in provides is the following:

- Management of appointments (an interval of time in which some kind of event occurs). Two types are distinguished: the *blocking ones* (shown on the left column of each day) that do not allow overlapping with others (like independent tasks) and the *non blocking ones* (shown on the right column) that can happen at the same time interval (like reminders).
- An intuitive GUI for user interaction (See Fig. 2) that allows introducing, checking, modifying and removing appointments as well as configuring the visualization properties (number of days, size, time intervals).
- The complete set of appointment configurations can be saved/loaded in a standard file format.
- Appointment booking negotiation that allows to reserve a set of intervals and confirm or refuse them later.
- A set of methods that allow searching the best free interval where an appointment fits, or retrieving the list of appointments contained in a given time range.

This plug-in has been included in both personal and doctor agents in order to manage their schedule during the booking negotiation. A detailed explanation of this process is made in §3.3.

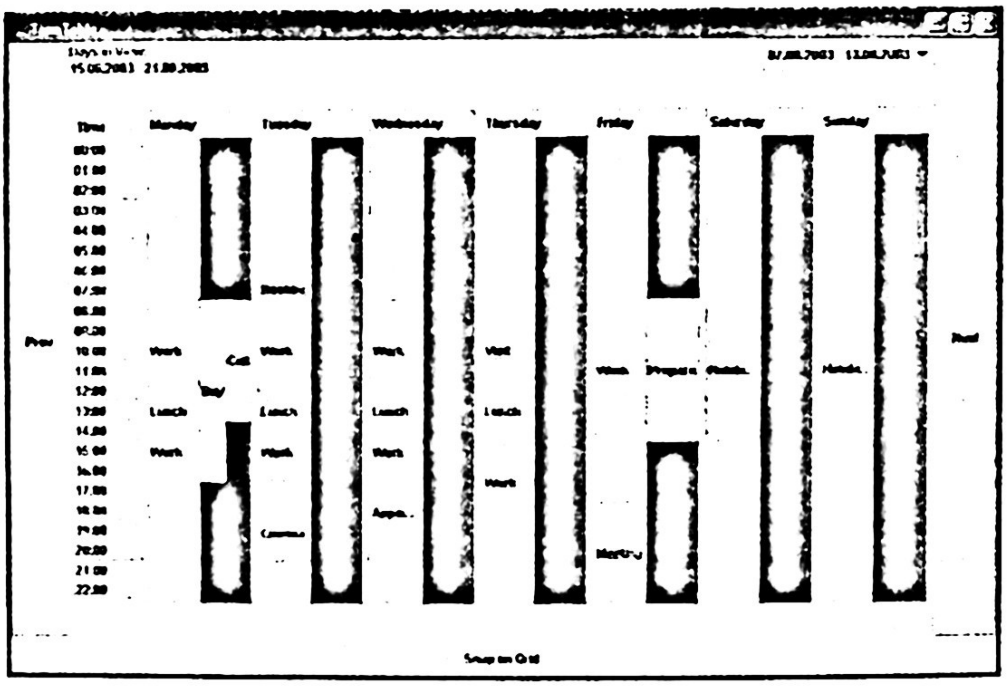

Fig. 2. Timetable plug-in GUI

3.2 Preferences plug-in

The *preferences plug-in* is a package which is able to manage multiple domains of preference. Its main goal is to allow to the user to obtain a ranking of a list of options (alternatives) according to the preferences of its corresponding domain.

Each domain (e.g. health care) has a set of criteria that corresponds to different properties or elements in the domain (e.g. doctors, cities). Each criterion can take different linguistic values to define the set of alternatives (e.g. doctors: Dr. Smith, Dr. Winston; cities: Tarragona, Barcelona). The user must express his preferences on these values. To do this, the user assigns a preference linguistic label to each of the possible values of the criterion (e.g. Tarragona=Best, Montblanc=OK, see Fig. 3). In addition, the user can indicate that one of the possible values of the criteria is not valid for him. For exanple, if the user does not want to be visited in a certain medical centre, he can assign a "Veto" label to this value (e.g. ConsultoriLocalAlforja=Veto).

Another feature of the plug-in is the possibility of giving different weights to each criterion. Moreover, some criteria can be temporally deactivated if the user decides not to take them into account for further decisions.

Once the user has specified his preferences, the plug-in can rank the alternatives taking into consideration all the criteria. To solve this problem a classical MCDM (Multi Criteria Decision Making, [14]) method has been implemented, which is based on multiattribute utility theory. This approach considers that each criterion is expressing a partial utility of each alternative. To aggregate these partial utilities, a weighted average is computed. Since the preferences are defined using linguistic values, a pre-processing stage is performed in which labels are translated into numbers. The result is a sorted and rated list of alternatives.

The plug-in has been integrated in the Personal Agent to sort the list of received proposals. They are sorted according to some criteria (e.g: place of the treatment, the name of the doctor, the medical centre) after a query for bookings has been performed.

As the user cannot know in advance all the possible values of the criteria (e.g: name of doctors or medical centres), the plug-in is able to discover new values each time that a query is performed. With this functionality the agent is able to learn from the user interaction and improve the quality of the rankings.

3.3 Booking negotiation

When the user needs the care of a doctor, he can book a visit using HeCaSe. The booking process requires the negotiation of many agents. So, this is the most complex process in the system due to its high level of customisation according to the user's profile and the number of agents that interact.

The protocol (see Fig. 4) is divided in several steps on which the data is processed from the most general to the most specific agent in order to achieve the best proposal that fits with the user's preferences:

1) Firstly, the user initialises a set of search constraints (medical specialty, urgency, number of desired proposals per doctor, number of days to consider

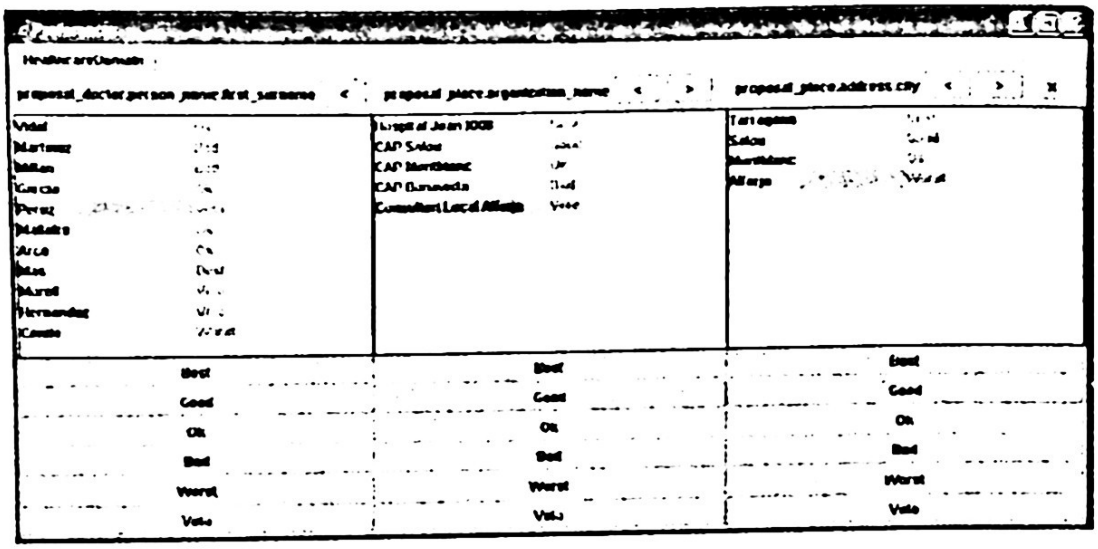

Fig. 3. Preferences plug-in GUI

and, optionally, the desired medical centre). Then the system analyses the user's timetable through the Timetable plug-in in order to find the best time intervals in which an appointment with a doctor could be set. To do this, it divides the following X days (the number has been given by the patient),into three intervals that are sorted according to the amount of free minutes inside them, preserving their natural order (position in time) in case of a tie. This represents the patient's wish to get an appointment in an interval that is as soon as possible and not already full with other appointments. With all this information, the Personal Agent (PA) constructs a message.

2) Secondly, the message is sent to the Broker Agent (BA) that broadcasts it to all Medical Centre Agents (MCA) or to the one selected by the user. The MCA fowards the message to the Department Agent (DEP) that fits with the selected medical speciality and finally, the DEP broadcasts it to all its Doctor Agents (DA).
3) Each DA evaluates the booking preconditions included on the received message and constructs a list of proposal appointments. In particular, the agent tries to fulfil the patient's wishes by matching the doctor's free time (determined by the timetable) with the sorted preferred intervals contained on the received message. If there is no possible slot in the most preferred interval or the user has requested more than one proposal, the doctor repeats the matching process with the next interval. The final proposed hours are reserved until the doctor agent receives the final accept or refuse message from the patient. This list of proposals of each doctor is returned to the DEP, which puts together all the doctors' proposals and sends them to the MCA. Then, all the MCAs involved on the protocol send their lists to the BA that joins them all and sends them to the user's PA.
4) Once this list is received, the PA evaluates the user's preferences (on the medical centres, cities and doctors). The Preferences Plug-in sorts and rates

the proposals (as described in §3.2) and the result is shown to the user. If some of the proposed appointments overlap with the appointments in the patient's timetable, the PA gives him a warning.

5) Finally, the user can select his preferred proposal or reject all of them. In the first case, the appointment is fixed on his timetable and an Accept message is sent through the medical hierarchy of agents to the desired doctor, and at the same time a Refuse one is broadcasted to the rest of involved agents; finally a confirmation is returned to the PA. In the second case, all agents receive a Refuse message.

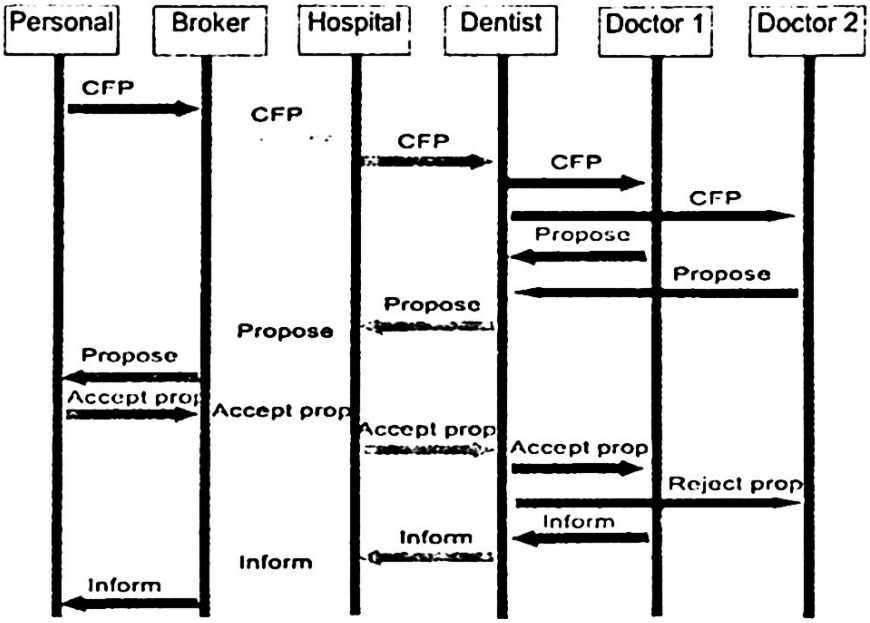

Fig. 4. 4-layer CFP Protocol for booking a visit

4 Security

In order to understand the role of security in the transmission of private and critical information (e.g. health records) through an open environment (e.g. Internet), it is necessary to define the concepts that determine the diverse security levels [6]:

- *Confidentiality*: is the property that ensures that only those that are properly authorised may access the information.
- *Integrity*: is the property that ensures that information cannot be altered. This modification could be an insertion, deletion or replacement of data.
- *Authentication*: is the property that refers to identification. It is the link between the information and its sender.

- *Non-repudiation*: is the property that prevents some of the parts to negate a previous commitment or action.

In the case of a MAS these properties are especially important, due to the autonomy and mobility of agents. A MAS without security support could not be used in an open environment such as Internet if it deals with critical data, because communications could be spied or the identities of the agents could be easily faked.

JADE-S [12] is a plug-in of JADE that allows to add some security characteristics in the development of MAS, so that they can start to be used in real environments. It is based on the Java security model ([11]) and it provides the advantages of the following technologies:

- JAAS (Java Authentication and Authorization Service)[1]: it allows to establish access permissions to perform certain operations on a set of predetermined classes, libraries or objects.
- JCE (Java Cryptography Extension) [2]: it implements a set of cryptographic functions that allow the developer to deal with the creation and management of keys and to use encryption algorithms.
- JSSE (Java Secure Socket Extension) [3]: it allows to exchange critical information through a network using a secure data transmission (SSL).

4.1 Basic Concepts

A JADE platform may be located in different hosts and have different containers. In order to introduce security in such an open and distributed environment, JADE-S structures the agent platform as a multi-user environment in which all components (agents, containers, etc.) belong to authenticated (through a login and a password) users, who are authorised by the administrator of the system to perform certain privileged critical actions. The general scheme of this environment is shown in Fig. 5. In each platform there is a permissions file that contains the set of actions that each user is authorised to perform.

Internally, an agent proves its identity by showing an Identity Certificate signed by the Certification Authority (provided in a transparent way to the agent when it registers in the system and provides the login and the password of its owner). Using these digitally signed certificates the platform may allow or deny certain actions to each agent.

4.2 Authentication

As explained above, each component of the platform belongs to an authenticated user. The user that boots the platform also owns the AMS and DF agents and the main container.

[1] More information at http://java.sun.com/products/jass/index-14.html
[2] More information at http://java.sun.com/security
[3] More information at http://java.sun.com/j2se/1.4/docs/guide/security/jsse/SEERefGuide.ht

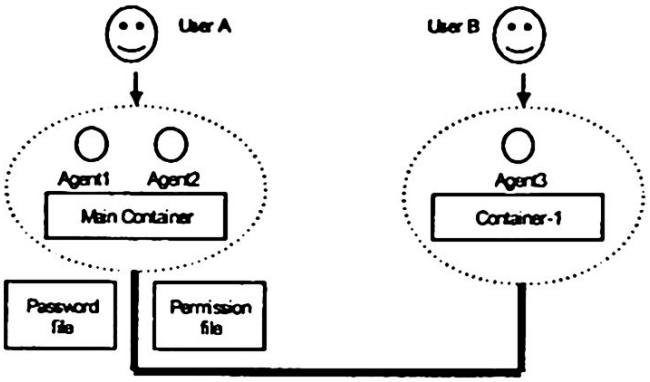

Fig. 5. General architecture of a secure agent platform

When a user wants to join the platform (through one of his agents), it has to provide his login and password. These data are checked with the passwords file contained in the platform, which is stored in a ciphered way, like Unix passwords. The passwords file is unique and is loaded with the main container.

Each agent owned by this user will have an Identity Certificate that contains its name, its owner and the signature of the Certification Authority.

4.3 Permissions and Access Restrictions

In a JADE-S platform the permissions to access resources are given to the different entities by following the mechanism defined by JAAS, the new system provided by Java, for user-based authentication.

Thus, it is possible to assign permissions to parts of the code and to its executers, restricting the access to certain methods, classes or libraries depending on who wants to use them. An entity can only perform an action (send a message, move to another container) if the Java security manager allows it. The set of permissions associated to each identity is stored in the access rights file of the platform (which is also unique and is loaded when the platform is booted).

Java provides a set of permissions (apart from those that may be defined by the user) on the basic elements of the language. Each permission has a list of related actions that may be allowed or denied (e.g. the `FilePermission` controls reading/writing/updating files).

4.4 Certification Authority and Certificates

The Certification Authority is the entity that signs the certificates of all the elements of the platform. To do that, it owns a couple of public/private keys so that, for each certificate, it creates an associated signature by ciphering it with its private key (which is secret). Then, when the identity of an entity has to be checked, the signature may be unencrypted with the public key of the Authority (which is publicly known) and we can check that the identity that the

entity wanted to prove matches the one provided by the Authority. The secure platform JADE-S provides a Certification Authority within the main container. Each signed certificate is only valid within the platform in which it has been signed.

4.5 Secure communication

In order to provide a secure communication between agents located in different hosts or containers, JADE-S uses the SSL protocol (Secure Socket Layer) that provides privacy and integrity for all the connections established in the platform. This is a way of being protected against network sniffers.

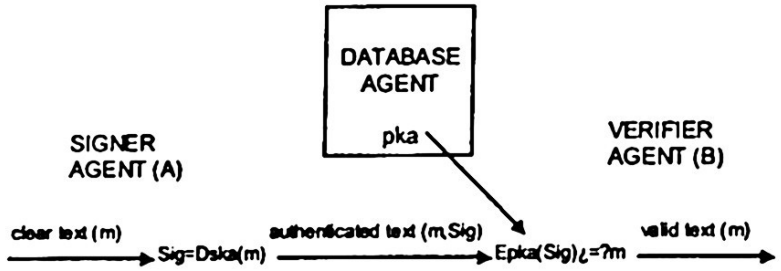

Fig. 6. Signing a message with a public key

4.6 Implementation

The main features of our security model are the following:

- All the messages exchanged among the agents are encrypted at the transport level with SSL, and the server is authenticated via an Authentication Certificate.
- We have established diverse security levels by using different user identities, and associating an owner (identified with a login and a password) to each agent (with a set of permissions for each one). Concretely, we have defined two virtual users associated to two groups of agents:
  - Internal agents: they execute inside the main container of the platform. We have linked these agents to the "root" user, which does not have any constraint.
  - External agents: they cover all the Personal agents that run from another host through an External Container. We have linked them to the "guest" user which has the minimum permission access (communication with the Broker Agent).
- It is a centralised access model through the Broker agent, that implements a software security control (See Fig. 1).

- Personal agents cannot communicate directly with any other agent (even with the DF).
- User authentication through the signature of critical messages using a public key mechanism (See Fig. 6).

5 Conclusions and future work

HECASE is part of the Agent Cities initiative ([1]) whose main aim is to provide agent-based services that improve the quality of life of the citizens and the visitors of a city. The deployed application certainly contributes towards this objective, by giving to the users the possibility of accessing medical data in an easy and efficient way.

This system is fully implemented in a prototype version, with all the agents running in standard PCs. The system has been designed to benefit two kinds of users:

a) Citizens that need medical services, who could access their medical record from anywhere, make appointments with a certain doctor based on his preferences, and obtain any kind of information related to the medical centres, departments and doctors of a given city.
b) Health care personnel, who could automatically access and update the patient's medical record during the examination, and would have their workload decreased, due to the fact that citizens could make queries or appointments on their own.

The system[4] described in this paper has been implemented using JADE [13]. The content of all messages is written in RDF ([4]). The medical records database has been implemented using MySql. Moreover, we use the plug-in JADE-S[5] and the cryptographical library Cryptonite ([5]) to provide a secure infrastructure in the platform [9].

Finally, we summarise some research lines to follow in the future:

- The test of the system with real data of medical centres, departments and doctors.
- The implementation of user agents deployed in mobile environments (such as PDAs or mobile phones). The LEAP library [13], compatible with JADE, may be used for this purpose.
- The integration of new agents that simulate other medical entities like Medical Service Agents (X-rays, clinical analysis ...).
- The use of medical guidelines to ease the doctors labour by proposing a set of actions or treatments to be followed for a medical problem.

[4] Our system is accessible live in the Agent Cities network of platforms (see access instructions at http://grusma.etse.urv.es/hecase/)

[5] JADE Security (JADE-S) is a plug-in and it can be obtained from the JADE's Website (http://sharon.cselt.it/projects/jade)

- The design of a hierarchy of Brokers that controls a subset of medical entities (e.g: medical centres located in the same city). We will study the coordination of these brokers in order to provide a more efficient solution instead of the centralised Broker approach.

Acknowledgements

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Agent-Based User Interface Adaptivity in a Medical Decision Support System

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Abstract. Previous work at Oxford Brookes University developed a system to advise on diabetes treatment that enabled data to be displayed according to the choices of each user. Due to the time critical nature of the problem, spending time searching through the data was not feasible. This reduced the usefulness of the system in the clinical setting for which it was designed. Thus a more automated approach was required. A multiagent system has been utilised to drive the adaptivity. A set of simple agents, each concerned with a single aspect of the system, communicate with each other and the suggested summary is a result of the emergent behaviour of the whole system. While emergent behaviour is used in other areas where agents have been applied, notably robotics, it is novel to use this approach in adaptive interfaces. This paper first considers the use of reactive agents to provide a context for the application of emergence in the area of self-adaptive interfaces. The field of adaptive interfaces is also considered to identify approaches that have been used in the past. An emergent multiagent system using a two-layer model is then described. This approach has been applied and tested to the problem of providing self-adaptivity at the interface to allow for decision support to be delivered in real-time for a clinician to employ.

1 Introduction

The work described in this paper is concerned with the provision of accurate dosage advice for diabetic patients. This project has produced a PDA-based system into which patients enter various details about their diet and physical condition and are given accurate dosage advice for the insulin that they require [1]. In collecting data from the user, this system is also a repository of information about the day-to-day condition of the patients.

As part of the project, a desktop computer based system was also developed to allow the data from the PDA to be made available to the clinician. This system provided the required data visualisations. However, the context in which it is used, that of a standard consultation, does not allow enough time for a clinician to access

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the data to find the salient information from a given dataset (a patient record) or browse the visualisations. The current project was undertaken to address this problem.

As the clinician did not have sufficient time to make use of a system that allowed them to analyse the data, it was decided instead to investigate the possibilities of developing a computer system that carried out the evaluation and allowed the medical professional to simply review what the system had produced. The constraints that had to be met were that the system should act in real time to find the interesting patterns in the data and then meet the individual requirements of each clinician. A prescriptive system that forced the user into a particular way of working would have been anathema to the work habits of clinicians, the intended users, so a system that could adapt itself to the work habits of the users was required. To this end, an adaptive interface was developed. This system needed to be capable of learning user preferences and relating them to the patterns in the data. The system was required also to provide a summary of the dataset in the form of a set of recommendations for data views. A multiagent system was developed to drive the adaptivity. A set of simple agents, each concerned with a single aspect of the system, communicate with each other and the suggested summary is a result of the emergent behaviour of the whole system.

2 Diabetes Mellitus

Diabetes mellitus is one of the most common acute diseases and affects a significant proportion of the population. The least severe form of the disease is known as impaired glucose tolerance. This may or may not develop into full-blown diabetes, which has two forms, type I diabetes and type II diabetes. Type II is less severe but more common, and is often treated by a strict diet and/or tablets. In some cases however, insulin replacement therapy may be required. In the case of type I diabetes, patients always requires insulin replacement therapy. Type I sufferers may experience some temporary remission during the early stages of the disease (known as the honeymoon period) but after this, they will require regular insulin replacement therapy for the rest of their lives.

Diabetes is a disease caused by the breakdown of one of the body's feedback mechanisms. Glucose (sugar) is the body's natural energy source. It is obtained from food and used throughout the body although primarily by the muscles and brain. While the liver plays a large part in the regulation and storage of blood glucose, it is insulin as produced by the pancreas that is the most important hormone.

As with all hormones, insulin is a messenger chemical that is secreted as and when needed by the body to create the feedback loop in a process. In this case it is concerned with the maintenance of the blood glucose level. When an excess of glucose is detected in the pancreas, insulin is secreted which promotes the transfer of glucose to cells. As the blood glucose level drops insulin production decreases and so the amounts of glucose present in the blood returns to normal. Another hormone glucagon performs the opposite task encouraging the release of glucose from cells when the level drops too low. This is normally a highly effective system with glucose concentrations kept at between 4 and 6 mmol/l.

In Type I diabetes, there is a major insulin deficiency and the level of blood glucose increases. The body attempts to remove some of this by excretion in urine. To attempt to compensate, the kidneys must work continuously to remove excess glucose and this produces the characteristic symptoms of increased urination and thirst. Eventually the body can no longer metabolise glucose and so must turn to another process to provide energy. This is achieved by the breaking down of fat cells. This highly inefficient process produces organic acids that provide an important alternative energy source for the brain when present in small amounts. In large concentrations, such as those observed in untreated Type I diabetes, these organic acids or ketone bodies accumulate in the blood stream and urine. They eventually reach a critical concentration and ketoacidosis occurs. This leads to coma and death.

By taking insulin, the diabetic patient can cause their blood glucose levels to reduce but if they take too much, the body's blood glucose level can drop too low again causing coma and death. Thus, keeping the blood glucose level at a safe level is a matter of maintaining a fine balance. Normally the body can modify its insulin and glucagon production as required to allow control at the level of relatively subtle shifts with the feedback systems in the body ensuring that this process can be carried out accurately. When insulin production is impaired and the patient must provide the necessary insulin themselves, it becomes more difficult to control the system as insulin will be taken at a few relatively fixed points in the day and feedback cannot be constantly provided and the first hint that the blood glucose level has moved out of range can be the onset of a hypoglycaemic reaction or 'hypo' when the body attempts to shut down.

Recent major studies have confirmed conclusively that the main aim of diabetes treatment should be to maintain the body's blood glucose level as near to the normal level as possible [2, 3].

In diabetic patients the body cannot produce its own insulin, so the patient is required to regularly take enough insulin to balance the blood glucose levels. This involves the patient in trying to determine how much insulin they will need based not only on the current blood glucose level but also considering various other factors. These include what, and how recently, the patient has eaten; to what intensity and how recently they have taken exercise; how they are generally feeling health wise; the time of day and whether their blood glucose has recently gone outside safe limits.

3 Diabetes Treatment System

The multiagent system described in this paper is part of a research and technical development collaboration with the Diabetes Trials Unit of Oxford University. The objective of the partnership is to allow diabetic patients, clinicians, diabetic nurses and researchers to interact efficiently and effectively with a highly integrated diabetes treatment system. The system architecture includes several interacting elements. The two core elements are the handheld diabetic patient insulin dosage advisor and the diabetes clinic decision support system described in this paper.

The portable advisor, POIRO Mk2, is based on the POIRO system developed by the collaboration [1]. POIRO proved highly effective and user friendly, but was

developed originally on a large and expensive hand-held computer, the Epson EHT-10. It was ported to the Apple Newton and subsequently to Palm OS® PDAs, incorporating significant improvements. The PDA system has recently completed a successful clinical study at the Radcliffe Infirmary in Oxford.

At a clinic visit the diabetic patient provides the doctor with details of their blood glucose levels, insulin taken, and 'hypos', recorded in a 'log-book'. However, these records even if completed in full - which is not universally the case - do not provide the clinician with information concerning the factors affecting the patient's metabolism when each glucose reading and corresponding insulin injection was taken. With the advent of the PDA based system, the diabetic patient now has an incentive to enter not only the data which the logbooks were designed to store but also background factors as these are needed to allow the system to make its recommendations. As part of its operation, the PDA-based system stores this information.

Diabetic Patients got on well with the PDA-based system in trials and when in use, the system amassed useful records not only of their glucose levels and insulin dosages but also collected data concerning some of the relevant environmental factors that influenced these. It was felt that if this information could be uploaded to a clinician's system, it could provide a great deal more information about the day-to-day condition of the patient than had previously been possible. To this end, a data visualisation package was created to allow healthcare professionals to view graphs and tables summarising the relevant points from the data.

One of the key features of a clinician/patient consultation is that it takes place over a very short time, perhaps between seven and fifteen minutes. As this is all the time available to the clinician with a patient to discuss how their health has been over the previous period of three to six months, there is insufficient time to allow for the use of the uploaded data, except for the more experienced clinicians. However, it is increasingly the case that diabetic patients are being treated by general practitioners or specialist nurses, who do not have the same level of experience and knowledge to interpret the data in the way that experienced clinicians are able to. Therefore, support in analysing the data was required.

It was considered necessary to automate the process of finding the relevant patterns in the data, so that the amount of time that was needed to make effective use of the system was reduced significantly. However, different clinicians work in different ways and might be interested in viewing the data in different ways too. They might even wish to view the data in differing ways for a patient different, which further complicates the issue. So while adding pattern finding functionality is a useful first step; because of the way that clinicians work and the very short time frame in which the interaction with each patient takes place, this in itself is not sufficient to make the system worthwhile. If time were not such an important factor, then simply producing a system that was customisable might be sufficient. The fact that a clinician does not have the time to spend customising a system means that any useful system had to be able to tailor itself to the clinician rather than relying on the clinician tailoring the system to their needs.

Our work investigates whether multiagent-based emergent adaptivity at the interface can produce useful and meaningful behaviour in the form of automatically adapting the system to the user. To achieve this, the system must be able to determine

the interests of the user and any patterns in the data that are relevant to those interests. These interests could vary as each patient is considered, so a system with the ability initially to learn a clinician's interests and then dynamically change the areas of interest to be investigated with each new set of data is required.

An adaptive approach was chosen to allow for the fact that there *are* patterns in the interactions of the users, that are different for different users. The time constraints put on clinicians , the target users provided one of the main considerations. That is,. The clinician needed to access the factors relevant to them in the data, taking the minimum amount of time from the consultation.

The initial focus of the work was on the needs of clinicians. However,, since the management of diabetes is changing, moving from hospital based treatment to treatment centred in Health Centres it is entirely possible that in the future other health care professionals might come to need access to the data provided. The system developed was thus required to accommodate to the needs of potentially disparate classes of users in addition to the variation within the initially considered user class.

In reviewing the requirements of the system, they were:

- to learn over time to both tailor itself to the user and to make its pattern identification effective.
- to cope with the sometimes short time scale of operation.
- to correlate between user actions and data patterns.
- any system suggestions should be an adjunct to the main operation so that the user could use or ignore them as they saw fit.

The idea of allowing the system to carry out part of the work, to have, as Wooldridge [4] suggests, agents in certain circumstances take the initiative rather than wait for users to say exactly what they require of the system, is very appealing. This is especially the case when one considers the perennial issue of the time constraints that clinicians are under. As the goal in this project was to allow the system to do the initial filtering work for the clinician, the idea of an agent-based approach seemed an appropriate one to consider.

4 An Agent-Based Approach

In his definition of intelligent agents, Muller [5] classifies agents into three main categories: reactive agents; deliberative agents and interacting agents. He then goes on to develop a taxonomy based on these three types and suggests the type of architecture that might be applicable for particular classes of problem. These classifications are worth a closer examination.

Reactive agents Muller defines as those that express reactivity and real time behaviour. Typically, these will have little if any explicit world model and will make decisions at run-time based on simple behaviour-action rules. Classically, this approach has been used in the field of robotics with Brooks subsumption architecture [6] being the ubiquitous example. This is a layered architecture where each individual entity is only concerned with a particular part of the task and it is through the combination of all the activity that the functionality of the whole system emerges. The idea of emergent behaviour is closely linked to this.

While an emergent behaviour approach is most closely associated with robotics research, it has had some application at the user interface. The work of Wavish and Graham [7] shows that reactive agents can produce interesting results in other areas. They have created systems with reactive agents as actors where the behaviour of the system emerges from the interactions of the 'actors'. This suggests that when it is possible to identify each important aspect in a system, agents concerned with each might be able to produce complex behaviour through their interaction.

This idea has been applied to the provision of an adaptive interface. Agent driven adaptive interfaces have been developed where the agents unobtrusively observe the user and make inferences based on the user's actions [8]. In our work, the idea of unobtrusively observing the user as a data source has been used but a community of simple agents has been employed where each is concerned with a particular facet of the interaction and the overall behaviour emerges

The classical approach to developing a system such as this is to develop explicit models of the various entities that the adaptive interface needs. Thus user models, task models and system models are developed. If such models were developed then it might seem logical to use a deliberative agent to control such a system, however, there are problems with this approach. The specification of the current system highlights two important issues. The first is that of speed. A large complex user model is less likely to be able to respond quickly to changes. In a system where the user's interaction with the system involves a series of short consultations, an unwieldy model is not the best choice. A more fundamental issue relates to the actual domain. As discussed above, the data that is now available and that this system is designed to display has not been available before. Thus while clinicians have a good idea about what is important, it is very possible that there are patterns and relations that can only be observed when the data now available is examined. Thus a system that can attempt to derive its own organisation for the data is going to be more useful than one where the relationships have to be explicitly described at design time as is the case with a high level model. For these reasons, it was decided to employ a system of reactive agents

5 The Multiagent System in Action

At the interface, there is a series of agents each concerned with a particular aspect of the functionality. Being simple reactive agents they are able to rapidly respond to changes. As noted above however, such simple reactive agents do not usually express complex behaviour. In this work, the agents are provided with the facility to adapt their reaction thresholds over time and by interacting extensively with other agents, produce through emergence a more complex system. From the point of view of the data, by using a series of reactive agents that are each responsible for a particular facet of the data (statistic derived from the data), such as means, upper and lower quartiles, and allowing them to build up relationships with other data agents, the system is able to self organise itself in such a way that it models the patterns in the data.

When attempting to work at a low level and provide adaptivity by carrying out observation at the level of individual actions, the complexity of the task becomes an important issue. Gervasio et al [9] found that when trying to predict the actions that a user carries out to create a schedule in a crisis planner, that by reducing the complexity of the task to be predicted - by abstracting classes of actions from the set of available actions - the accuracy of prediction increased. Of course, this increases the workload for the user, as they are required to provide the specific details to the action predicted. This raises the issue of just how effort should be divided between user and computer in such a mixed initiative system.

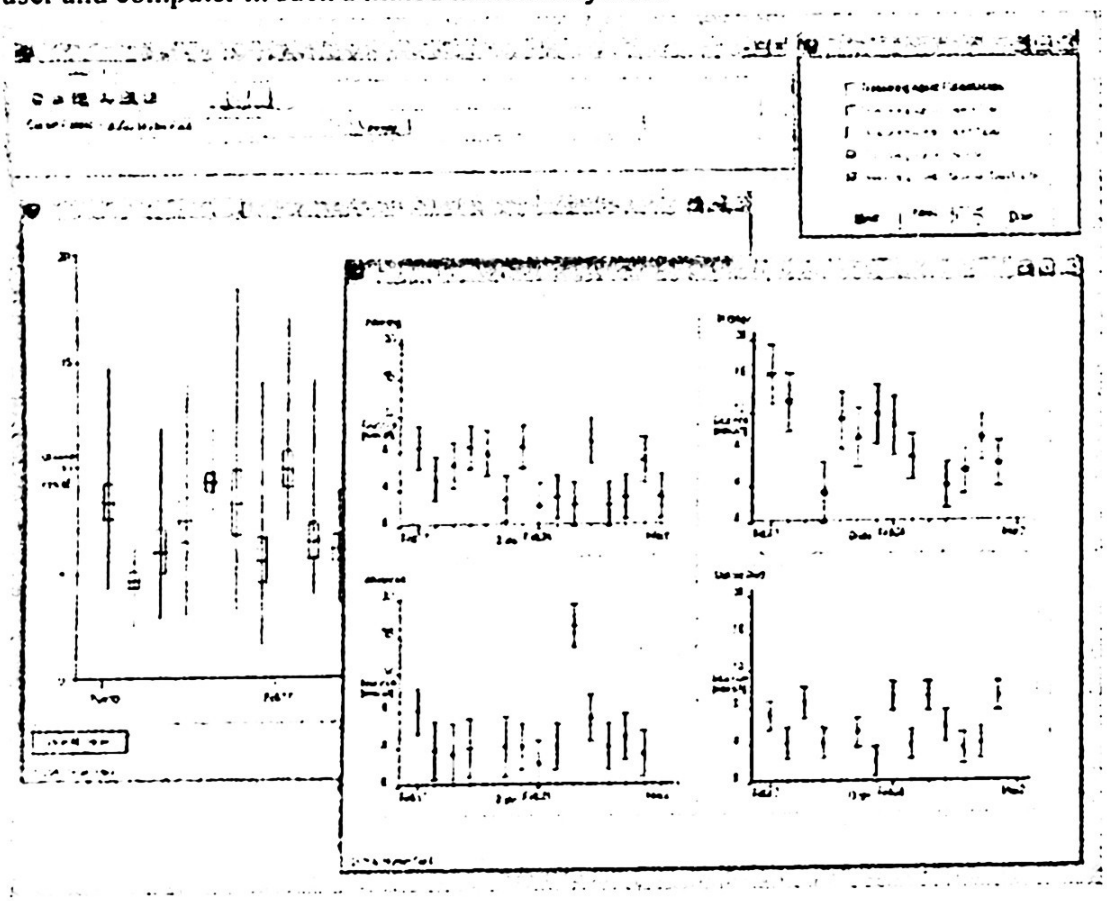

Fig. 1. The Multiagent system in action

The goal in providing adaptivity is to make the user's task easier rather than to actually replace the user. In a mixed initiative system, the user should still maintain control and the system should be simply trying to reduce the complexity of the user's task rather than taking them out of the loop completely. With this in mind, it is perfectly feasible to produce a system that meets the more limited goal of making it easier for the user to obtain the commands they wish to carry out rather than to predict with complete accuracy each command .With this objective, the proposed adaptivity in the system involves a dynamically generated set of options that reflect important aspects in the data available. The system simply provides these options to the user; the user is then free to take or ignore these choices, thus maintaining control. Crucially system generated choices save the user from having to analyze the data to make the choices themselves.

Figure 1 illustrates the interaction from the user's point of view. The interaction follows these stages:

- The user logs in.
- The user selects a patient which causes the patient's dataset ('log-book' record of PDA recorded events) to be loaded, having been either previously or immediately downloaded from the patient's PDA.
- The dataset is analysed (i.e. data agents compute data attributes).
- The user can either select one or more of the system's data visualisations via the system's menu or select a 'summary' – the summary is a prioritised list of the systems visualisations.
- If the user selects the summary, this can be stepped through to display each in turn (the user can select the length of the list from one to the complete list of 16 visualisations).

6 System Architecture

There are two layers to the architecture produced. The interaction layer contains the agents that interact with the data and the user and brings the results of the interactions together to allow decisions to be made. The control layer contains the agents that manage this process. In addition, a blackboard contains a discourse model to record user actions and a domain model to capture relationships between interface actions and dataset attributes. A blackboard is employed to communicate models because the system is using reactive agents that do not have the facility to store large amounts of data.. Figure 2 shows the system architecture and how the two layers of agents operate within the system.

6.1 The Interaction Layer

The main part of the functionality of the agent component is found in the interaction layer. The agents here are responsible for interacting with both the user and the data and combining the information from both to make the decisions about the summary that is to be generated. The task to be completed has two distinct parts. As data arrives, it needs to be analysed for patterns and as the system is used, the interface has to monitor the actions of the user, i.e. choices of visualisations. These are very different tasks. Monitoring the data is a discrete process that is carried out whenever a dataset is loaded whereas monitoring the user is a continuous process. It therefore makes sense when employing a community of agents to employ one set to act in a discrete manner and deal with the dataset while another acts in a continuous manner and deal with the actions of the user. While the data and the interface are monitored separately, each needs to feed into the other. Thus an effective way of combining the information from the data and the interface is needed. To allow this, a third set of agents is required that communicates only with other agents. These bring together the information from the data and interface agents in such a way that the patterns in the

data can be used both to drive what is important in the summary and to provide a context for the actions that the user is taking.

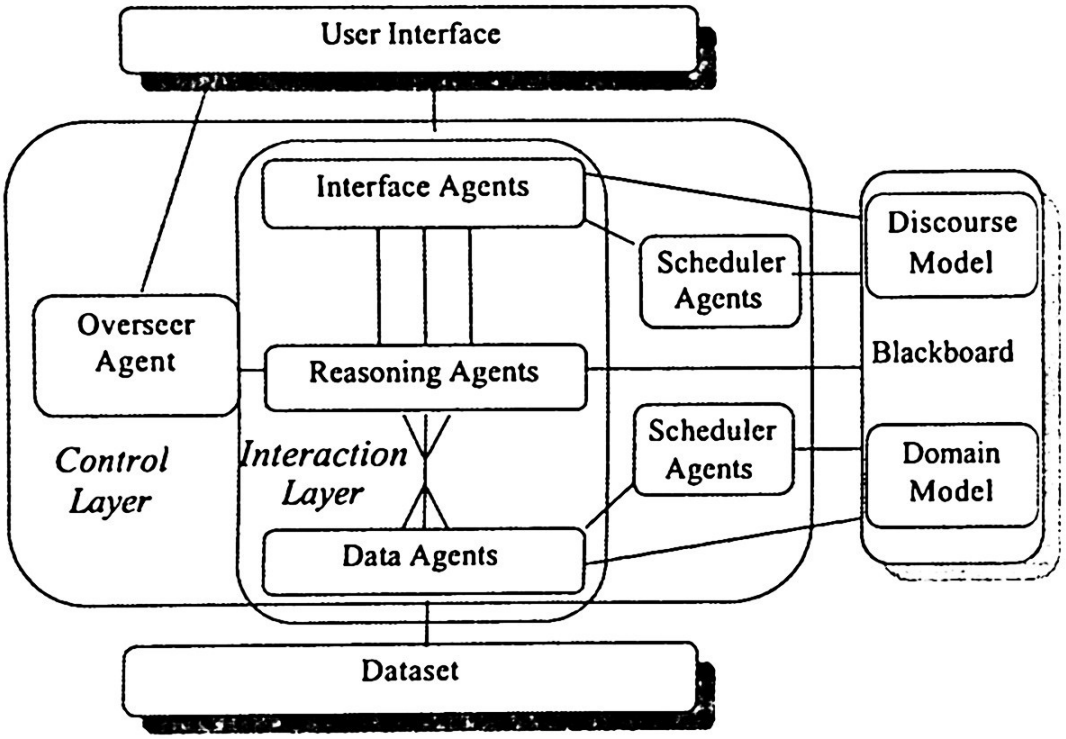

Fig. 2. The Multiagent system architecture

6.1.1 Interface Agents

There is an interface agent associated with each of the relevant interface actions. When the user carries out an action, the relevant interface agent notices this and keeps track of this occurrence. It then looks to see which interface actions preceded it and which follow it. This information is used to update its model about sequential relationships between the action it is associated with and other interface actions. This information can be supplied to the relevant reasoning agent when required. In this way, each interface agent is responsible for building a model of how important its own action is and how it relates to other interface actions.

6.1.2 Data Agents

When a dataset enters the system, some initial calculations are carried out to enable the system to assign attribute values to the dataset. At this time, the data agents will also examine the data. Each data agent is concerned with a particular attribute of the data and looks to see whether the data's value is different from what it normally expects. If the value is beyond a threshold above or below normal, the agent will notify this fact. It will then look to see which other agents have also notified. By taking note of which agents have notified each data agent can build up its own local model of how other data aspects relate to its data attribute. This allows the community

of data agents to track correlations and inverse correlations. As with the interface agents, this information can be provided to the reasoning agents when required.

6.1.3 Reasoning Agents

Reasoning agents do not have any direct contact with the users or the data. Instead they combine the data from interface and data agents. Interface agents can determine patterns of behaviour in the actions of the user and data agents can determine patterns in the data. By combining these, the reasoning agents have a fuller picture of the situation. When the data agents are notifying about changes in behaviour, the reasoning agents take note of this. They also take note of when their associated interface action takes place and look for correlations between the use of their interface action and changes in the data. When a summary is requested, each reasoning agent will attempt to make a case for its interface action. It does this by interrogating its associated interface agent about the associated interface action and by interrogating the data agents to decide whether the current data patterns match with the correlations that it has developed. This information allows the reasoning agent to decide whether its interface action's priority in the 'summary' should be amended (up or down). Once each reasoning agent has made an initial case for its interface action, it can check the strength of belief that other reasoning agents have of their actions and use the information from the interface agent to decide whether to update its belief because of the level of belief in other interface actions to which there appears to be a correlation.

6.2 Control Level

If one allows a community of agents to alter their behaviour then there is a danger that the system's behaviour will migrate away from what is required. To address this, the control layer has final control over any changes made and so can ensure that the actions of the agents stay within sensible bounds. An overseer agent is responsible for this. In a community of agents there is also the issue of coordinating the communication that takes place. Again the control layer takes responsibility for this by providing scheduler agents to mediate the interaction where required.

6.2.1 Overseer Agent

The role of the overseer is to keep the system within sensible bounds. This is something that could have been achieved by coding limits into the interaction layer agents themselves or by providing an overall arbiter. It was decided that a central arbiter was a more sensible choice as the control was being applied to the overall decisions being made rather than the individual parts of the process. In a system that utilizes emergence, trying to effectively constrain the system by considering it at an individual agent level would be a difficult task without affecting the ability of the agents to effectively collaborate. Thus providing the control at the community level was implemented as a more transparent way or providing the necessary functionality. The overseer agent responds to the user's request for a 'summary' by interacting with the reasoning agents to compile a prioritised list of visualisations.

6.2.2 Scheduler Agents

Facilitating the interchange of information in the system are the scheduler agents. While the individual agents can in many cases interact sufficiently without outside interference, it is sometimes the case that an outside entity is required to control part of the data flow. For this reason, scheduler agents are responsible for mediating various parts of the interaction. An example of the use of a scheduler agent is when an interface agent is activated and adds the fact that its action has been chosen into the discourse model. It can then look back over the discourse model to see which actions were carried out previously and use this information to update its model of action sequences. Each agent also needs to know which actions happen after their own action to allow for sequences going forward in time. To provide for this, the interface agents could remain watching the discourse model and take notice of every time a new action was added. This means that a number of agents will be spending time simply accessing the discourse model to see what was happening. However we have seen that it is more efficient to have a single scheduler agent tasked with watching the discourse model and keeping track of which agents' actions have occurred and taking responsibility for sending information to each agent when further actions occur.

7 Discussion

The system has been informally evaluated in a clinical setting in consultations between health care professionals and diabetic patients. Three health care professionals used the system and reported that they found the information provided useful. They also reported that they did not find the system intrusive, one clinician reporting that he had viewed the information in one session with a patient but had not found the information useful in this particular instance, importantly he said that had not felt that it had wasted his time asking for the information. All users reported that the system delivered the information in a timely manner and did not detract in any way from their interaction with their patient. In addition, they stated that if the system were made available for their use they would use it in the majority of the sessions they had with patients.

When creating a system such as this, it is very important that the system is able to make accurate judgments as to what the user wants. As discussed, this has been achieved through observing the user choices in response to the data available. In itself, this might seem a logical start but a feedback mechanism is needed to allow it to appraise effectiveness. Using agents to check how the user utilizes the summaries provided achieves this by analysing choices from the summary in the same way that the choices from the main interface are analysed. This allows the system to determine how accurate the summary is. Just as choices made at the interface provide data for adaptation, advice followed, and indeed advice not followed provide the feedback loop to keep the system in check. The control layer agents keep the actions of the agents within sensible bounds but this in itself does not prevent the agents making incorrect choices. Providing an effective feedback mechanism goes towards addressing this problem.

Currently, the feedback mechanism uses whether or not the choices from the proposed summary were selected to provide the information. If the user selects something that is available from the summary directly from the interface, it does not consider the ramifications of this in terms of acceptance of the summary. An analysis of this type involves a much deeper study of the user interface issues surrounding the use of a system of this type. While worthwhile, it is beyond the scope of the current work.

A second issue when considering accuracy of decisions made is the quality of the information upon which the decision was made. Many adaptive systems do not have a strong model of exactly what the user is trying to achieve. A good example of this is the work of Korvemaker and Greiner [10] where they were trying to predict Unix commands. They demonstrated that a system could, in the case of Unix command prediction, attempt to predict the pattern of commands that is to be repeated. However, this does not mean that one can necessarily have any understanding of what the user is trying to achieve. Without this knowledge, the task of prediction is, as shown, very difficult. In the case of web page prediction, the various systems can attempt to match keywords in the available pages to pick their recommendations. This could be seen as starting to move towards trying to understand what the user is trying to achieve and perhaps make it easier to then predict what they require from the system. The agents have some idea about what each page is concerned with and user choices allow them to determine what type of page is of interest. Of course the use of keywords is not perfect. Unfortunately HTML based pages do not allow for much else. With more widespread use of the various XML related technologies [10], we could perhaps be moving towards a situation where much richer knowledge about what the user is attempting to retrieve is available. This could be used to enable agents to produce better-informed choices about what is required.

In our system, a conscious effort is made to try to make the most of the available information from both data streams. The actions of the user are considered alongside patterns in the data. This allows the system to not only observe patterns in what the user does but relate these to the data being considered thus placing these actions within a context.

By using a community of simple agents that communicated with each other, it was possible to consider the actions at the interface and the patterns in the data separately while still having a mechanism in place in the form of the reasoning agents, which allowed these two analyses to be combined to provide the final decisions.

8 Conclusion

This work demonstrates that the use of emergent behaviour in a community of agents provides a means of driving a self adaptive system. To achieve this using a conventional approach would have required the construction of a far more complex system with the various high level models that such an approach entails. We have shown that a group of agents working at finding patterns can combine together through their interactions to produce a working system. With the relationships

between the various patterns in the data and user actions implicitly modelled, one can, at least in some cases, avoid the need for complex high level models.

Hence the agent-based system adapts to the clinician's usage, rather than to his or her implicit directions, in order to provide the clinician with high quality information in a form that is pertinent to their enquiries yet unobtrusive in use.

9 Acknowledgement

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Designing Community Care Systems with AUML

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Abstract.

This paper describes an approach to developing an appropriate agent environment appropriate for use in community care applications. Key to its success is that software designers collaborate with environment builders to provide the levels of cooperation and support required within an integrated agent–oriented community system. Agent-oriented Unified Modelling Language (AUML) is a practical approach to the analysis, design, implementation and management of such an agent-based system, whilst providing the power and expressiveness necessary to support the specification, design and organisation of a health care service. The background of an agent-based community care application to support the elderly is described. Our approach to building agent–oriented software development solutions emphasizes the importance of AUML as a fundamental initial step in producing more general agent–based architectures. This approach aims to present an effective methodology for an agent software development process using a service oriented approach, by addressing the complex agent environments decomposition, abstraction, organization and software development process activities characteristics, whilst reducing its complexity of the agent–based by exploiting AUML's productivity potential.

1 Introduction

The providers of public and private sector health care services have, in recent years, been faced with some radical changes in the society they serve (Peckham et. al., 1996). This paper considers why agent technology may be useful in developing a service-oriented approach to the provision of community care where multiple services have to interact to provide an effective and efficient service. While many of the services are provided by physical agencies through programmes of visits, information technology can do much to reduce social isolation by providing a range of information services (SeniorWatch, 2000) which can be integrated so that they are effective and usable by the client.

Community health care is dynamic, complex and progressive. Its aim is to provide such services as are necessary to maintain a client's quality of life in the community when they are unable to provide for themselves, thus maintaining their independence. Provision is delivered by a wide range of disparate, independent organizations and agencies, each having their own objectives, of which the provision of community care is typically only a part. The objective is to integrate these services with their other responsibilities in a coherent and efficient manner (Beer & Huang, 2002). Agent-based community care services are a new approach that automates the process of linking constituents with

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their core competencies quickly and effectively on the Internet. Important aspects of this development include the need to:

- use agent–oriented architectures, models and methodologies to create flexible roles,
- add and delete services as required,
- more closely model the integration of separate services and,
- dynamically change the relationships among services as conditions change.

Huang et. al. (1995) introduced an agent–based distributed medical care system which allowed patients' own needs to guide their individualized care management. The community care service agents are able to not only support traditional services but also provide a range of utility services such as individual care planning, health service advice, customised information filtering etc., all of which are intended to maintain the client's integration into the community. In the real world, individual care providers currently use their own heterogeneous databases, workflows and command and control systems with little or no integration between them (Beer et. al. 2003). This causes difficulties, not only in the provision of the most effective response to emergencies, but also in the management of routine care as the client's requirements change, often quite rapidly. Current systems do not provide the flexibility to allow such changes to be implemented as rapidly as one would desire. This is because an Individual Care Plan is specified by the Social Services Department of the Local Authority. It then contracts various agencies to actually deliver the various components of the care as appropriate. There is therefore no single agency with the overall authority to plan, manage, deliver and monitor the provision of community care. To this must be added the various health care services, and the emergency services, each of which acts independently and have their own independent records and command and control structures but are essential components in the delivery of the total package (Beer et al. 2001). Similarly, there are the large numbers of informal carers (family, friends, neighbours etc.) who are currently almost totally ignored by the system, but who also provide invaluable support.

In this paper we describe the principles behind a distributed Agent-Based Integrated Community Care (INCA) system. A demonstrator system, implemented using the ZEUS agent-building toolkit (Nwana et al., 1999) is also described in order to demonstrate the feasibility of the approach and its potential practical benefits. This demonstrator shows that the technologies proposed allow effective communication without compromising integrity and privacy. In particular they allow an approach to be taken that allows minimum collection of information in that the Home service agent can be configured so that it only releases private or sensitive data in case of an emergency, when such information is of value.

The objective of the INCA Project is to investigate how community care can be developed in the internet age through the use of multi-agent technology. The motivation for this has been a consideration of the agent society's social abilities in:

- Promoting effective care systems that:
    - provide better services and resources to clients,
    - enhance social interaction between them, and with their carers
    - deliver more effective care
- Providing the high-abstraction level care management strategies by linking all relevant agencies into a single framework of accountability.
- Giving an in-depth understanding of the health information framework that underpins the delivery of high quality, effective community care, including the formularization of the links between the disparate agencies involved.
- Establishing a single Agent-Based care monitoring facility that can be used by all care

professionals to assist in effective monitoring and diagnosis.

- Developing cooperative structures within the community structures to change service provision and care policies through the use of automated agent involvement in planning, scheduling, organizing (both formal and informal) care and even directing care service programs.
- Devolving care management and responsibility to those providing the care by providing shared supervision and teamwork and by separating the organizational from the social requirements, developing a much more responsive and client centred environment that adapts rapidly to changing needs.

Some of these objectives have already been investigated in the medical domain through the use of multi-agent system architectures. For example, the GUARDIAN system (Hays-Roth & Larsson, 1996) considered patient monitoring in a Surgical Intensive Care Unit. Support is provided for collaboration among specialists, each an expert in a specific domain but fully committed to sharing information and knowledge among each other and the nurses that continuously monitor the patient in the physicians' care. A system devoted to diabetes care has been presented, where cooperation not only between the medical specialists, but also others, such as administrators is supported within the agent community (Lanzola et al., 1995).

A more general Agent-Based telemedicine framework has been reported (Dela Mea, 2001) that can assist specialists in diagnosing difficult cases through information sharing, cooperation and negotiation. In this case each specialist has their own Tele-medicine-Oriented Medical ASsistant (TOMAS) agent that behaves as a medical assistant and has two generic functions:

- an agenda for managing appointments, and
- methods for access to patient records.

Support for tele-medicine is provided through the remote exchange of patient data, cooperative annotation of cases and negotiation of appointments. These approaches have been greatly assisted by moves to standardize medical information through the formalization of patient and other records (Department of Health, 2001). Some of the flexibility offered by the mobile access to records and services is being demonstrated by the Ward-in-Hand project (Ancona, 2001), but only in the relatively restricted environment of a conventional hospital ward.

The INCA project aims to take these forward from the purely medical domain and integrate them into the general community care environment, where the linkages are less formal and effective cooperation and negotiation is essential if appropriate care is to be delivered. A major difference is that it is rarely possible to share information as freely as within the purely medical domain because of the involvement of different agencies and individuals with widely differing requirements. The agent community therefore has to act as a coordinator and filter to ensure that appropriate and correct information is distributed to all concerned. Also, since help is likely to have to travel some distance it is often better to provide whatever assistance is readily available in a timely manner, rather than the optimal solution that may arrive too late.

2 The INCA Demonstrator

The demonstrator uses multi-agent technologies to enhance the mechanisms for the systematic and widespread assessment of the health of the elderly out-side of a conventional clinical care regime. Enhanced assessment provides a valuable and timely source of information and knowledge that enables the optimization of care provision and management. Non-invasive assessment technology provides a source of health information that is well suited to identifying subtle, yet important,

changes in an individual's condition. This can then be combined with appropriate knowledge sources available elsewhere on the agent network to trigger pre-emptive care and treatment (Haigh & Yanco, 2002). Appropriate care is then be provided in an effective and timely manner.

It aims to improve:

- Current community care systems by using agent-oriented engineering solutions to design a new cooperative, coordinated, collaborative health care e-service by the adoption of agent-oriented models, platforms and methodologies.
- Coordination between social services and medical care services, organizing and managing these concurrent actions in an effective and inter-operative way.
- The provision of positive assistance to maintain and enhance the quality of service and the provision of routine care as specified by the Individual Care Plan.
- The integration of services by adopting a service oriented approach

INCA provides a complex community care service by using Agent technology solutions to organize and allot limited resources and services to a large number of care requirements. From the released work, it became clear that to maximise the effectiveness of agent–oriented community services activities, it would be prudent to have clear methods and models for analyzing, designing, organizing, controlling and managing agents' cooperation, communication and interaction.

3 Agent-oriented UML and its Concepts

AUML (Parunak & Odell, 2001) (Bauer et al., 2001) provides a new way of thinking about agents and how they interact with each other and their environment. Unified Modelling Language (UML) is a de facto industry standard established by (Booch, 1999) that:

- presents a form of notation for object-oriented analysis and design;
- provides system architects working on objects analysis and design with one consistent language for specifying, visualizing, constructing and documenting the artefacts of software systems, as well as for business modelling (OMG, 1999).

UML provides a designable meta-model that represents a collection of semantic models including static models, dynamic models, usage models, and architectural models. All the models can be constructed, viewed, developed and even evaluated during the time of systems analysis and design. provides A semantics package is provided, which allow UML model elements and notations to work independently within different packages for different processing, as shown in Figure 1.

This aspect of the software development approach (e.g. representational formalism) leads us focus on using UML notations to represent Agent concepts (e.g AUML), when redesigning and reorganizing the existing Community Care & Alarm Services systems.

The use of Agent-oriented UML provides a formal platform for analyzing, designing, organizing, managing agent behaviours and modelling an agent-based system. In order to fully exploit the flexible behaviours and productivity potential of agents, AUML was selected to assist INCA process for agent system design and development.

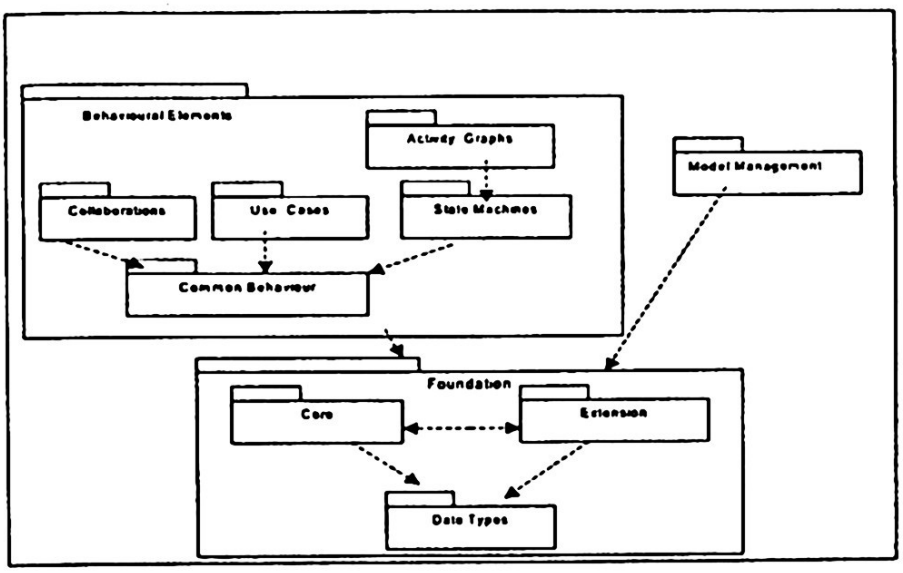

Figure 1. UML: Package Structure (OMG, 1999)

4 INCA System Design and Development with AUML

After considering agent concepts at an abstract level, the next step was to develop a practical design and implementation for INCA systems through the use of agent-oriented Unified Modelling Language (AUML)

First, it was necessary was to analyse all the needs of an agent–oriented community care environment and analyse the requirements with the agent models. This stage would identify the agent-based roles from all of the available care service resources (including description and identification of the agent tasks, health services and components). In practice, community care agents in INCA system could be as described in Table 1, based on the UML Use Case models (Beer et al, 2003).

During the INCA System development, agent-based UML semantics and notations were used to address the overall architectural complexity across agent domains by using a set of UML graphical diagrams, such as use-case diagrams, class diagrams, agent behaviour diagrams and implementation diagrams. The sample diagram (Figure 2) is a notation diagram of Agent-based health care Service Supplyi, which shows how a series of co-operational agents gathering domain operational information achieve their tasks and domain goals. The model begins with roles/agent initiation and definition, and moves to the roles 'planning for supplying emergency service' and organizing agent behaviours, relations and responsibilities, followed by loading some particular class requirements. Finally, this model provides a small autonomous agent domain to generate operations such as an executable service package to users.

NAME	DESCRIPTION
Care Co-ordinator	The agency responsible for providing the range of services necessary to ensure that the Client is properly cared for. The Care co-ordinator is responsible for preparing a Care plan and for monitoring its effectiveness in meeting the needs of the Client. This is often the Local Authority or some other official body with a legal duty to provide the necessary care.
Care Provider	The various agencies and individuals responsible for providing the care specified by the Individual Care Plan. This will include Social Workers, Health Care Professionals, Care Assistants, Emergency Services, and Social Services etc. who can provide an extremely wide range of care services, if required.
Informal Carer	The various relatives, friends, neighbours etc. who provide some form of support and assistance in an informal way (i.e. outside the Individual Care Plan), but it is often essential to allow the Client to remain resident at home. This is often flexible and responsive and can range from totally unstructured and so not recognised at all in the Individual Care Plan through to fully recognised and integrated with the efforts of the professional carers.
Client	The person who lives in their own dwelling (either an ordinary house or a sheltered home) and who receives a package of community care services. This package may range from very minimal interventions, such as social alarm systems, through to an intensive mix of community support services.
Emergency Services	This agent provides appropriate assistances and services during the emergency events. This is often flexible and responsive and through to fully recognised and integrated with the efforts of the professional emergency supports such as Ambulance, Hospital, Fire Service Department etc.

Table 1: The sample of community care agents in INCA system (Beer et. al., 2000)

AUML is much more than a program language and modelling design diagram. It is concerned with agent domain architecture modelling and it provides a range of declarative models. Functionally, UML is a key ingredient in generating agent architecture and approaches to the agent system devolvement processes in detail and it is able to provide the instruction and design platforms by defining all variant and invariant roles of the agents describing their attributes and dynamically organizing pre and post conditions for operations.

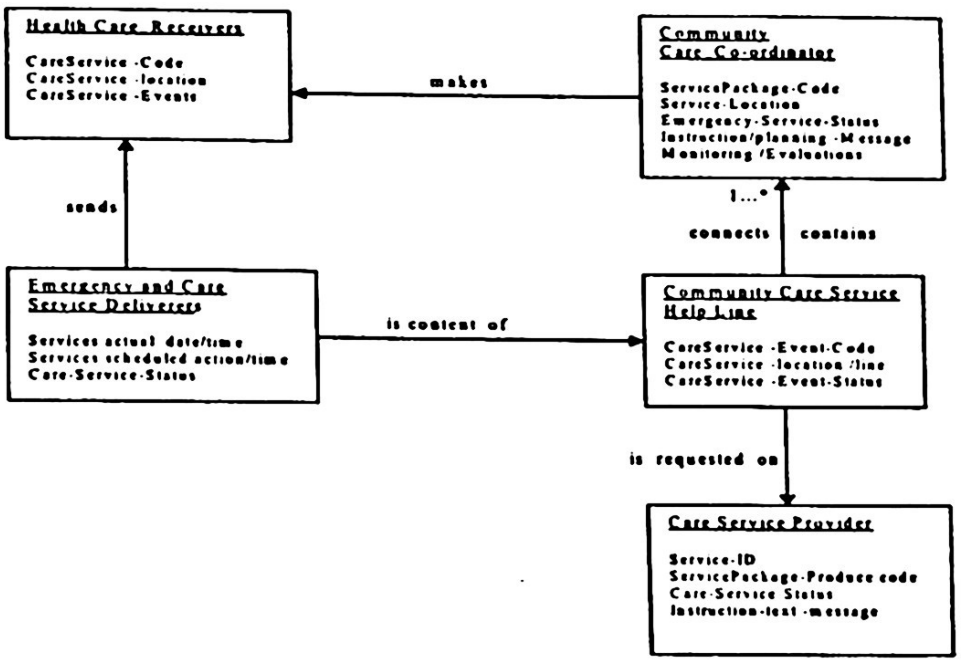

Figure 2: AUML real-time notation diagram of Community Care Services Supply

Agent-oriented UML is a modelling platform that describes the formal specification of the function, structure and behaviour of agents and multi-agent system. It has three main categories for describing system artefacts and information; static, dynamic and descriptive (OMG, 1999). Each category solves a type of domain problem. The classification is given in Table 2.

Category	Artifacts
Static	class, package, components and diagrams
Dynamic	Use-cases, interaction (sequence, collaboration, state chats, activities diagrams
Descriptive	Class descriptions

Table 2. UML artefact categories (OMG, 1999)

An agent-oriented UML model represents the static category by describing agent requirements in detail such as classes, packages, diagrams and components. The dynamic artefacts describe the communication among the components inside a shared common agent system. Descriptive artefacts are used with the other diagrams to support the description of information represented in different perspectives. The diagram below is an AUML-Use Case diagram of Community Care Service Scheduling [Figure3], which is a modelling diagram representing the technical roles and routing of community service supply. It allows knowledge-level agents to be linked efficiently and to share and exchange resources in a common communicated agent architecture and to achieve the "Rational Effect" domain goal.

The next stage is modelling, which involves gathering a range of state of the art techniques and

models for communication, interaction, coordination and control. It can be divided as the *interaction model* and *acquaintance model* (communication, conversation policy, appropriated protocols and negotiation rules among agents). This model represents the technical roles that allow knowledge-level agents to be linked efficiently and to share and exchange resources in common agent architecture. Such interactive community care supply routing can be seen in Figure 4. This is an example of providing care services routing, which illustrates that both official and unofficial care producers/agents (such as *Care Provider, Inform Care, Care Co-ordinator*) could provide an individual care plan and community care services for Clients through the negotiation agents.

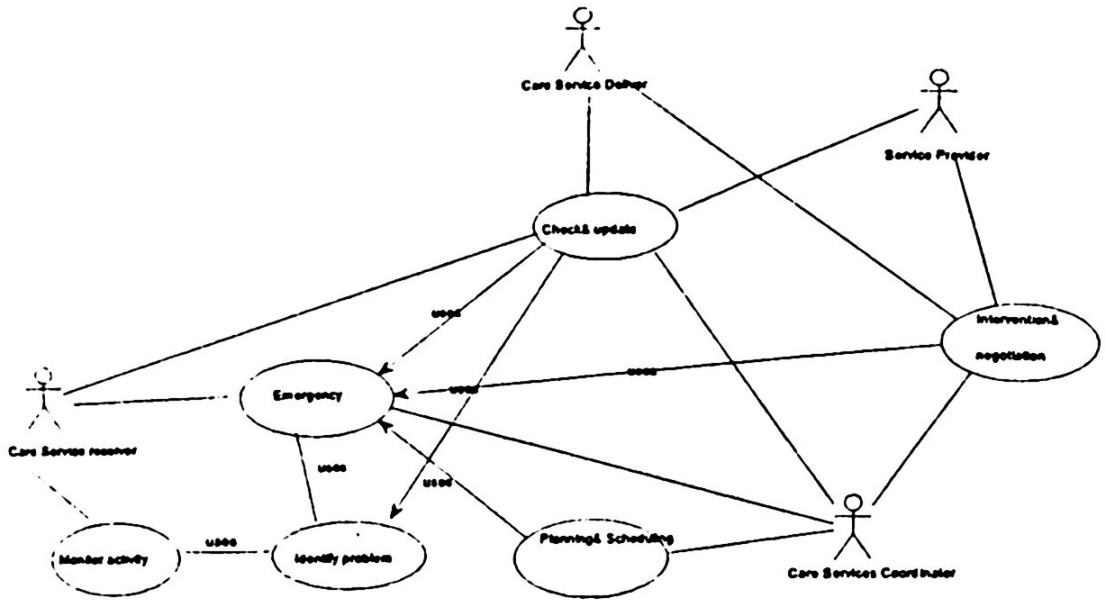

Figure 3: AUML: Use Case diagram of Care Services Scheduling in INCA system

Once the individual care plan has been established, care services required to assist the Client must be managed and controlled by the agent system. Such interaction demands communication messages to be passed and routed as shown in Figure 5.

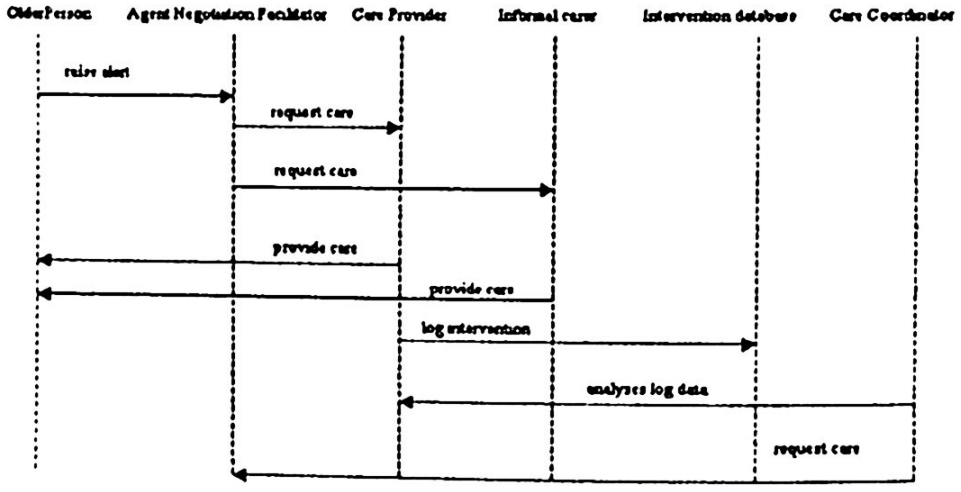

Figure 4: AUML: interaction diagram of an individual care plan and communication routing for older person

Furthermore, the main contribution of AUML to INCA work is the attempt at making the design and development of a multi-agent system as simple as possible. It greatly simplifies the configuration and organisation of agents, the endowment of communication capability and the cooperation capability of agents. This is achieved by mimicking real-world solutions to the current care service activities [Figure 6].

5 Conclusions

The development of Agent-oriented community care systems unveil many unexpected challenges and opportunities to create more advanced distributed e-service systems by fully using agent capabilities and responsibilities using a service oriented approach. This allows us to develop new service styles which lead to reduced costs, improved communications and affect the way we live, work and do business. For example, this paper considers the issues associated with community care of the elderly and infirm. This is only one of a range of care services and we are now using the same methodology to consider the issues associated with child protection. In some cases the same services can be used, while in others new ones need to be developed to meet the different needs. Considerable savings could result from sharing services when appropriate.

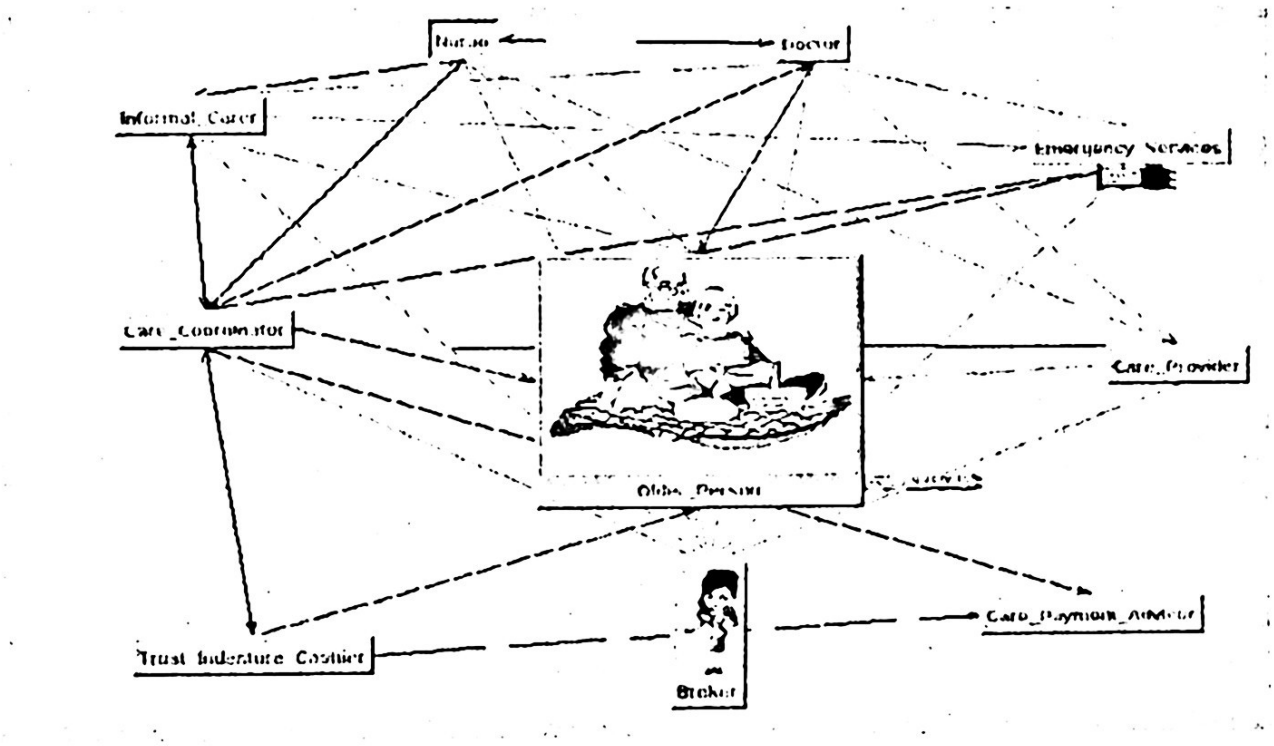

Figure 5: Community care service message passing and interactive routing

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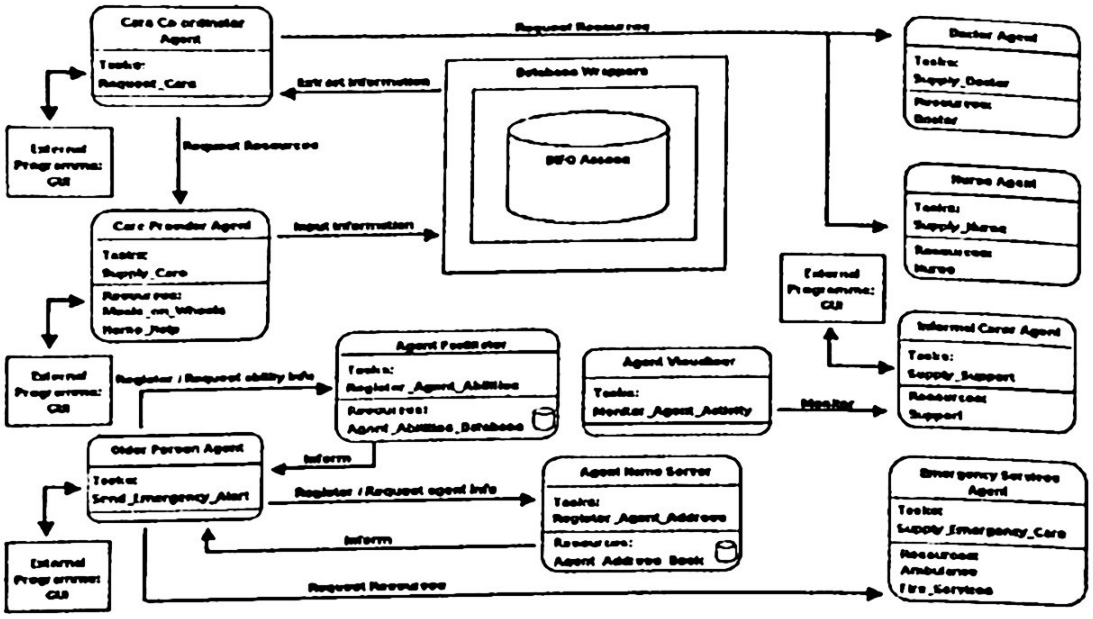

Figure 6: The Overall Architecture of the INCA Prototype

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Integrating the organ and tissue allocation processes through an Agent-Mediated Electronic Institution

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Abstract. In this paper we present a first approach to the formalization of Carrel, a virtual organization for the procurement of organs and tissues for transplantation purposes, in order to model the allocation processes of organs and tissues in a integrated way. We show how it can be formalized with the ISLANDER formalism. Also we present a first mechanism to federate the institution in several geographically-distributed platforms.

Keywords: Electronic Institutions, Multi-agent systems, Transplants.

1 Introduction

Organ transplantation from human donors is the only option available when there is a major damage or malfunction in an organ. At the time of writing, more than one million people in the world have successfully received an organ, and thereafter, in most cases, lead normal lives.

Over the years, transplant techniques have evolved, knowledge of donor-recipient compatibility has improved and so have immunosuppressant drug regimes, leading to an increase in the number of organs that can be transplanted, but also in the range of transplants, moving beyond organs (heart, liver, lungs, kidney, pancreas) to tissues (bones, skin, corneas, tendons). However, the allocation process for tissues is quite different from that for organs, because of the time such pieces can be preserved outside the human body. Tissues are clusters of quite homogeneous cells, so the optimal temperature for preservation of all the cells composing the tissue is almost the same. Thus, tissues

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can be preserved for several days (from six days in the case of corneas to years in the case of bones) in tissue banks. For tissues, the allocation process is triggered when there is a recipient with a need for a certain tissue, at which time some number of tissue banks are searched for a suitable one.

Organs, on the other hand, are very complex structures with several kinds of cell types with different optimal preservation temperatures. That fact leads to quite short preservation times (hours), no need for an organ bank, and an allocation process that is triggered when a donor appears, taking the form of a search for a suitable recipient in some number of hospitals.

1.1 The case for software systems for organ and tissue management

The increasing rate of success of tissue transplants is leading to an increase in the number of requests. This volume is starting to overwhelm the human coordinators and furthermore is leading to tissue loss, because available tissues are not being assigned due to lack of time to process all requests.

In the case of organs, successful transplants have also led to an increase in demand for organs for transplantation purposes. However, there is not an increasing volume of donations to match the demand. Much research has been done to create policies for donor identification (to increase the number of available donors), organ allocation (to find a suitable recipient for each organ) and in extraction, preservation and implant procedures (to increase the chances of success).

The relative scarcity of (organ) donors has led to the creation of international coalitions of transplant organizations. This new, more geographically distributed, environment makes an even stronger case for the application of distributed software systems to solve:

- *the data exchange problem:* exchange of information is a major issue, as each of the actors collects different information and stores it in different formats. The obvious, and easily stated, solution is the definition of standard data interchange.
- *the communication problem:* countries typically use different languages and terminologies to tag the same items or facts. Either a standard notation or a translation mechanism needs to be created to avoid misunderstandings.
- *the coordination issues:* in order to manage requests at an international level, there is the need to coordinate geographically distributed surgery teams, and to coordinate piece delivery at an international level.
- *the variety of regulations:* an additional issue is the necessity to accommodate a complex set of, in some cases conflicting, national and international regulations, legislation and protocols governing the exchange of organs. These regulations also change over time, making it essential that the software is adaptable.

The first two points can largely be resolved using standard software solutions. For instance, the EU projects RETRANSPLANT, TECN have devoted most of their effort to the creation of a) standard formats for the storage and exchange of information about pieces, donors and recipients among organizations, b) telematic networks, or c) distributed databases. Another project, ESCULAPE, uses conventional software to help in matching tissue histocompatibility.

The third point (coordination) is harder to solve with conventional software. A sound alternative is the use of *software agents*, where an *Agent* is a computer program capable of taking its own decisions with no external control (*autonomy*), based on its perceptions of the environment and the objectives it aims to reach [18]. It not only reacts to the environment (*reactivity*) but also *proactively* takes initiatives. The *social ability* of agents allow them to group together (in *agencies*) sharing common objectives and dividing the tasks to reach those objectives. All these attributes suggest that multi-agent systems are well-suited to solve coordination issues.

It is the last point (the variety of regulations changing over time) which underpins our case for the use of so-called *electronic institutions*, whose purpose is to provide over-arching frameworks for agent interaction, where agents may reason about the norms [6, 2, 3, 5], in the same way as physical institutions and social norms do in the real world. Electronic institutions and the norms that govern them are the key to a system that is able to adapt automatically to changes in regulations.

In summary, our proposal address all four issues, by the use of multi-agent technology, not only for coordination and regulation but also serving as a language interface among teams using different terminology, and actively distributing the information to be shared.

2 An Institution for the distribution of organs and tissues

The Carrel institution is an agent platform which hosts a group of agents (an *agency*) responsible for the allocation of organs and tissues. In the case of tissues, the allocation process comprises:

1. The tissue banks keeping the institution updated about tissue availability
2. The agency receiving requests from the hospitals for tissues. For each request (brought by an agent representing the hospital) the institution tries to allocate the *best* tissue available from all the tissue banks that are known.

In the case of organs, the process comprises:

1. Each hospital informing the institution about patients that have been added to or removed from the waiting list of that hospital, or patients either to be added to or removed from the national-wide Maximum Urgency Level [1] Waiting List.
2. When a donor appears, the hospital informs the institution of all the organs suitable for donation in the form of *offers* sent to the organ allocation organization, which then assigns the organs.

Figure 1 depicts all the entities that interact with the Carrel system. There are a) the hospitals that create the tissue requests b) the Tissue Banks, and c) the national organ transplantation organizations, that own the agent platform and act as observers—the figure shows the organizations in Spain: the Organización Nacional de Transplantes [2] (ONT) [14] and the Organització CATalana de Transplantaments [3] (OCATT). In the proposed system all hospitals, even those owning a Tissue Bank, should make their

[1] In Spain the Maximum Urgency Level is called Urgency-0

[2] National Transplant Organization

[3] Catalan Transplant Organization

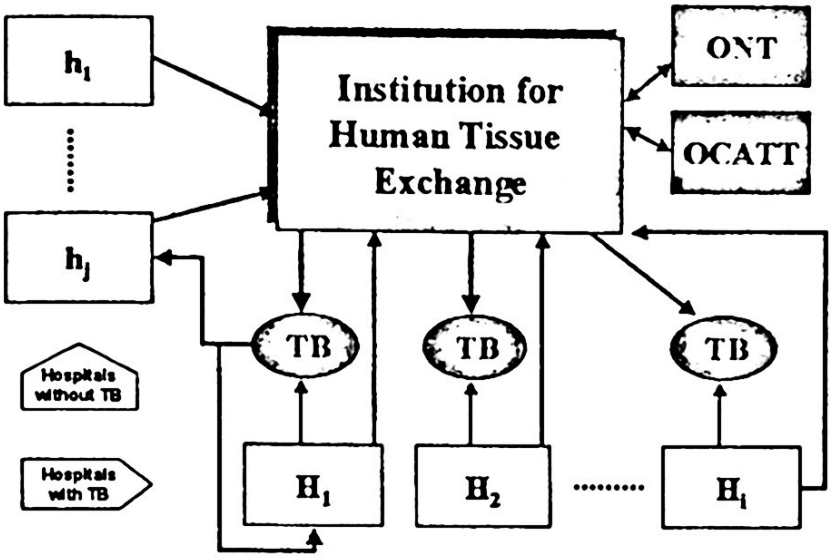

Fig. 1. Carrel: An Agent Mediated Institution for Tissues Assignment

requests for tissues or their organ offers through Carrel in order to ensure a fair distribution of pieces and to ease the tracking of all pieces from extraction to implantation, as the ONT and OCATT currently require for organs.

2.1 Role of the Carrel Institution

The role of the Carrel Institution can be summarized by the following tasks:

- to make sure that all the agents which enter into the institution behave properly (that is, that they follow the behavioral norms).
- to be up to date about all the available pieces in the Tissue Banks, and all the recipients that are registered in the waiting lists.
- to check that all hospitals and tissue banks fulfill all the requirements needed to interact with Carrel.
- to take care of the fulfillment of the commitments undertaken inside the Carrel system.
- to coordinate the piece delivery from one facility to another.
- to register all incidents relating to a particular piece.

2.2 The UCTx Agency

The participation of hospitals in Carrel is based on the notion of membership. That is, hospitals belong to the Institution and respect the negotiation (assignation) rules, and the agents that represent them inside Carrel are unable to break these conventions. A Hospital interacts with Carrel through the Transplant Coordination Unit Agency (*UCTx*). A version of the UCTx agent architecture that handles tissue requests can be found in [4].

Adapting the UCTx agency in order to assist not only in the tissue allocation process but also in the organ allocation process is not difficult. In the case of tissues, it is surgeons who are responsible for creating the tissue requests through their **Surgeon Agent** [4]. In contrast, for organs it is the *Hospital Transplant Coordinator* who is responsible for issuing organ offers to the institution or answering a call for recipients. So the architecture presented in [4] does not need to be modified but instead just the functionality of the **Coordinator Agent** is extended.

3 Formalizing the Carrel institution

To give a formal description of the interaction among agents in the Carrel system we will follow the ISLANDER formalism [7]. It views an agent-based electronic institution as a type of *dialogical system* where all the interactions inside the institution are a composition of multiple dialogic activities (message exchanges). These interactions (called *illocutions* [13]) are structured through agent group meetings called *scenes* that follow well-defined protocols.

3.1 The performative structure

The connected graph of scenes constitutes the *performative structure*. It is a network of scenes that defines the possible paths for each agent role. In accordance with its role, an agent may or may not be permitted to follow a particular path through the performative structure, and ultimately, may be required to leave the institution.

In the case of the Carrel institution, the set of scenes to model the organ and tissue allocation processes is:

- *Reception Room*: is the scene where all external agents should identify themselves in order to be assigned the roles they are authorized to play. If these agents carry either a request for one or more tissues or an offer of one or more organs, then this information is checked to make sure that it is well-formed.
- *Consultation Room*: is the scene where the institution is updated about any event or incident related to a piece. Agents coming from tissue banks should update the institution about tissue availability, while agents coming from hospitals should update the institution about the waiting lists and also inform it about the reception of all pieces (organs or tissues) they have received, the transplant operation and the condition of recipients.
- *Exchange Room*: is the scene where assignation of pieces takes place. There are specific exchange rooms for tissue requests (*Tissue Exchange Room*) and for organ offers (*Organ Exchange Room*).
- *Confirmation Room*: is the scene where the provisional assignments made in one of the exchange rooms are confirmed, whereafter a delivery plan is constructed, or cancelled, because a new request of higher priority has arrived.

A key element of the ISLANDER formalism is the definition of agent *roles*. Each agent can be associated to one or more roles, and these roles determine the scenes an agent can enter and the protocols it should follow (the *scene protocols* are defined as multi-role conversational patterns). There are two kinds of roles: the *external roles*

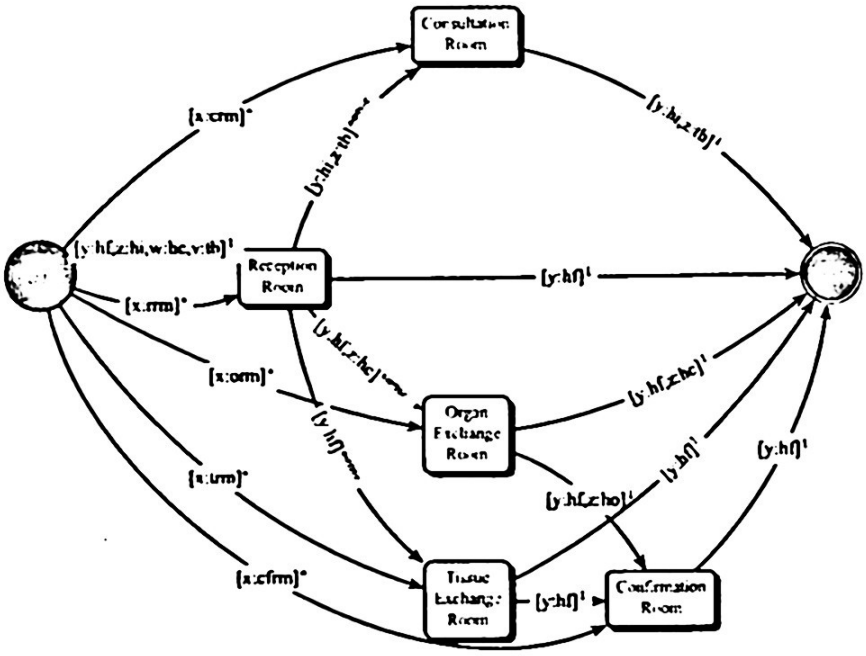

Fig. 2. The Carrel Institution performative structure

(roles for incoming agents) and the *institutional roles* (roles for agents that carry out the management of the institution). The external roles are the following:

Hospital Finder Agent **(hf):** agents sent by hospitals with tissue requests or organ offers that are seen from the point of view of the institution as requests for finding an acceptable tissue or recipient, respectively.

Hospital Contact Agent **(hc):** agents from a certain hospital that are contacted by the institution when an organ has appeared for a recipient on the waiting list of that hospital. The agent then enters the institution to accept the organ and to receive the delivery plan.

Hospital Information Agent **(hi):** agents sent by hospitals to keep the Carrel system updated about any event related to a piece or the state of the waiting lists. They can also perform queries on the Carrel database through the **DB Agent** (see §3.2).

Tissue bank notifier **(tb):** agents sent by tissue banks in order to update Carrel about tissue availability.

The institutional roles consist of one agent to manage each scene and one agent to coordinate all the scene relationships:

Institution Manager **(im):** agent coordinating all the scene managers.

Reception Room Manager **(rrm):** manager of the *Reception Room* scene.

Tissue Exchange Room Manager **(trm):** manager of a *Tissue Exchange Room* scene.

Organ Exchange Room Manager **(orm):** manager of a *Organ Exchange Room* scene.

Confirmation Room Manager **(cfrm):** manager of the *Confirmation Room* scene.

Consultation Room Manager (crm): manager of the *Consultation Room* scene.

With all the scenes and roles identified in the previous section, the performative structure can be drawn, as depicted in figure 2. Nodes are the scenes listed above plus *enter* and *exit* nodes which define the begin and end points of the diagram. Arcs are labelled with tags *variable:role*, where variable is an agent$_i$ and role is one among the identified Carrel's roles. The diagram in figure 2 shows, for instance, that scene's managers go directly from the *enter* point to the scene they should manage (the * means that they are the ones creating the scene), while all the external agents must proceed through the *Reception Room* scene in order to be registered and then be directed to the proper scene according to their roles.

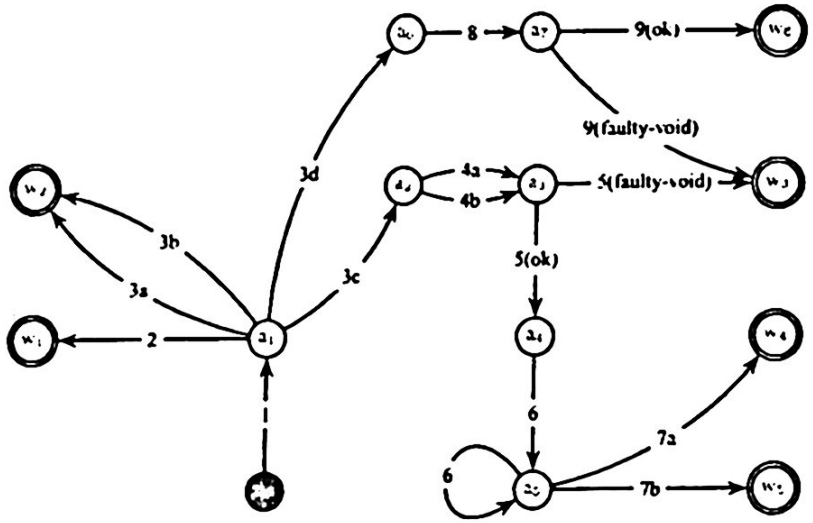

Fig. 3. The conversation graph for the Reception room

Authentication of external agents As explained above, in the *Reception Room* external agents enter and are registered inside the platform. In this room an authentication mechanism based in electronic certificates ensures that external agents come only from authorized organizations (which previously received the electronic certificate to be used). Once the sender has been identified and authorized, the external agents are then directed to the proper room according to their roles.

The protocol of this scene can be seen in figure 3: an agent$_i$ requests for admission (1) and may be accepted (messages 3a, 3b, 3c, 3d) or refused (message 2, exit state w_1). According to the role of the incoming agent$_i$:

- it is headed to the *Consultation Room* (exit state w_2),
- if it brings a request from a hospital, the request is checked (messages 4 and 5). Then agent$_i$ waits until the appropriate *Exchange Room* is available for the assignation (messages 6 and 7a for tissues, 6 and 7b for organs).

– if it was called by the institution to receive an organ offer, the information it brings about the recipient is checked and, if all is correct, it is then directed to the *Organ Exchange Room* that sent the call.

The content of the messages that appear in this conversation graph and the following ones are specified in [16].

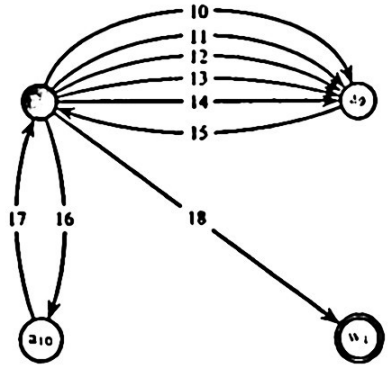

Fig. 4. Conversation graph for the Consultation room

Registering the recipients and the available pieces In order to manage the assignation of organs and tissues, the Carrel institution needs up to date information on a) all the available tissues for transplantation, b) the state of hospitals waiting list for each kind of organ, and c) the whereabouts about all pieces that have been assigned by Carrel.

The *Consultation Room* allows agents coming from hospitals or tissue banks to keep Carrel updated about all the facts mentioned above. The protocol of this scene is shown in figure 4. The incoming agents can perform notifications (messages 10 to 14) and are informed if the notification is successful (message 15). The agents coming from hospitals—which represent the Hospital Transplant Coordinator [4]—can also perform queries (message 16) about historical facts (e.g. statistics on, say, successful cornea transplantations over a certain period). The queries are answered (message 17) with the level of detail that is permitted for a certain role, as all access to the database is controlled through a *Role-Based Access Model* [10]. When the incoming agents have performed all the queries and notifications, they exit the Carrel system (message 18).

Allocating organs For organ assignment, a new scene, the *Organ Exchange Room* has been added. The protocol of this scene, depicted in figure 5, can be divided in two parts:

– the arrival of an Agent$_i$ (hospital *Finder Agent*) with an offer of an available organ (states a_{11} and a_{12}), waiting for a notification that a proper recipient has been found (message 22, exit state w_3) or not (message 27 leading to an exit request through state w_1).
– the loop of the scene manager looking for recipients. Based on the information of the waiting lists stored in Carrel's database, the scene manager sends a call to a

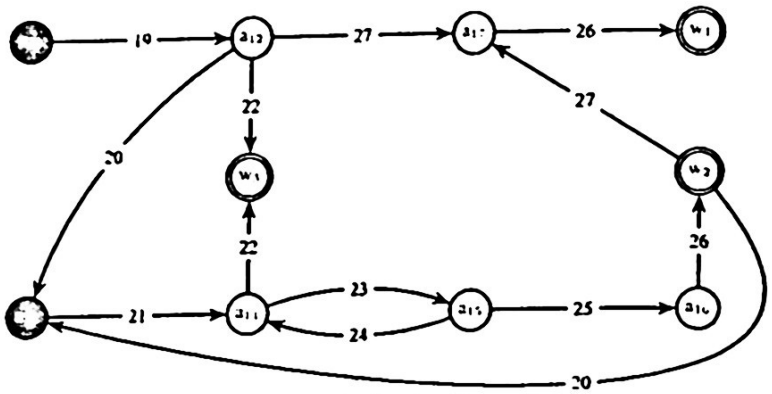

Fig. 5. The conversation graph for the Organ Exchange room

hospital (message 20) where there is a suitable recipient. Then an Agent$_j$ (hospital *Contact Agent*) enters the scene to answer the call, saying whether it accepts the organ or not (message 20). Sometimes Agent$_j$, representing the hospital Transplant Coordinator, expresses the intention to use the organ in a different recipient (message 23), a change that, depending on the reasons given, can either be accepted or rejected (messages 24 and 25). If the scene manager and Agent$_j$ agree, then Agent$_i$ is notified of the recipient, otherwise Agent$_j$ exits the scene and the loop starts again with a call to another hospital for another recipient.

The search and assignment processes by the scene manager are driven by knowledge of donor-recipient compatibility that is coded in the form of rules such as the following ones for kidneys:

```
1- (age_donor <= 1)
     -> (age_recipient < 2)

2- (age_donor > 1) AND (age_donor < 4)
     -> (age_recipient < 4)

3- (age_donor >= 4) AND (age_donor < 12)
     -> (age_recipient > 4) AND (age_recipient < 60)

4- (age_donor >= 12) AND (age_donor < 60)
     -> (age_recipient >= 12) AND (age_recipient < 60)

5- (age_donor >= 60) AND (age_donor < 74) AND (creatinine_clearance > 55 ml/min)
     -> (age_recipient >= 60) AND (transplant_type SINGLE-KIDNEY)

6- (age_donor >= 60) AND (age_donor < 74) AND (glomerulosclerosis <= 15%)
     -> (age_recipient >= 60) AND (transplant_type SINGLE-KIDNEY)

7- (age_donor >= 60) AND (glomerulosclerosis > 15%) AND (glomerulosclerosis <= 30%)
     -> (age_recipient >= 60) AND (transplant_type DUAL-KIDNEY)

8- (weight_donor = X)
     -> (weight_recipient > X*0.8) AND (weight_recipient < X*1.2)

9- (disease_donor Hepatitis_B)
     -> (disease_recipient Hepatitis_B)

10-(disease_donor Hepatitis_C)
     -> (disease_recipient Hepatitis_C)

11-(disease_donor VIH)
     -> (DISCARD-DONOR)
```

```
12-(glomerulosclerosis > 30%)
     -> (DISCARD-KIDNEY)

13- (HLA_compatibility_factors < 3)
     -> (DONOR-RECIPIENT-INCOMPATIBILITY)
```

Rules 1 to 8 are related to size compatibility, either considering age ranges (rules 1 to 7) or weight differences, here the criterion permits a 20% variation above or below. Rules 5 to 7 consider quality of the kidney and assess not only the limit that is acceptable but also the transplant technique to be used (to transplant one or both kidneys). Rules 9 to 10 are examples of diseases in the donor that do not lead to discarding the organ for transplantation, if a proper recipient is found (in the example, a recipient that has had also the same kind of hepatitis B or C in the past). Finally, rules 11 to 13 are examples of rejection rules, as determined by current medical knowledge.

It is important that such policies not be hard-coded in the system, as such rules evolve with practice (for instance, some years ago donors with any kind of Hepatitis were discarded). Expressing the knowledge in the form of rules is a technique that allows the system to be adaptable to future changes in medical practice.

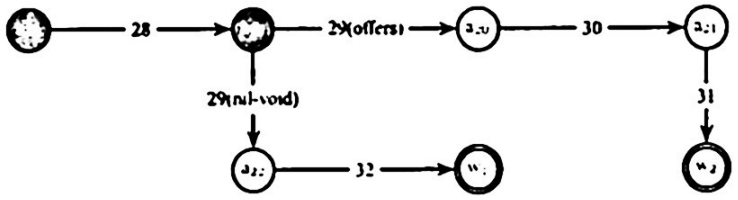

Fig. 6. The conversation graph for the Tissue Exchange room

Allocating tissues The *Tissue Exchange Room* is the place where negotiation over tissues is performed. The protocol of this scene is shown in figure 6: Agent$_i$ (hospital *Finder Agent*) asks the scene manager for tissue offers (tissues matching the requirements included in their petition). Then the scene manager gives a list of available tissues (message 29) that is evaluated by the external agent$_i$ (message 30). With this information the scene manager can make a provisional assignment and solve collisions (two agents interested in the same tissue). When this provisional assignment is delivered (message 31) then agent$_i$ exits the scene to go to the *Confirmation Room* represented by state w_2. There is an alternative path for the case when there are no available pieces matching the requirements described in the petition (message 9 with null list). In this case agent$_i$ requests an exit permission from the institution (message 32, exit state w_1), including the reason for leaving. The reason provided is recorded in the institution logs to form an audit trail for the relevant authorities to inspect. For further information about this negotiation process see [17].

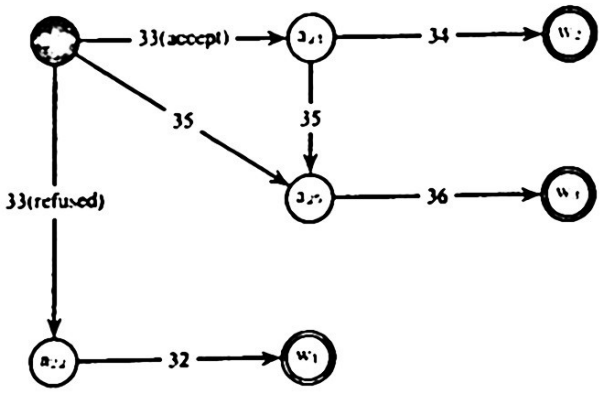

Fig. 7. Conversation graph for the Confirmation room

Confirming the assignation In the *Confirmation Room* scene, the provisional assignments made in a *Tissue Exchange Room* or an *Organ Exchange Room* are either confirmed or withdrawn. Figure 7 shows the protocol of this scene: the agent$_i$ can analyze the assigned piece data and then accept or refuse it (message 33). If the agent$_i$ accepts the piece and no higher-priority requests appear during a certain time window then the provisional assignment is confirmed and a delivery plan is given to the agent$_i$ (message 34), and then it exits the Carrel system (exit state w_2). When there is a request with higher priority that needs the piece provisionally assigned to agent$_i$ a conflict arises. To resolve the conflict the scene manager notifies the agent$_i$ that the assignment has been withdrawn (message 35) and that he is then entitled to a fresh request for another piece, if available, (message 36) to be negotiated again in the *Exchange Room* whence it came.

3.2 The Multi-agent architecture

The agent architecture that performs the *institutional roles* is shown in figure 8. There is one agent managing each of the scenes: the **RR Agent** managing the *Reception Room*, the **CR Agent** managing the *Consultation Room*, an **ER Agent** for each *Exchange Room* (either the ones for organs or the ones for tissues), and a **CfR Agent** managing the *Confirmation Room*. Also there is an agent (the **IM Agent**) playing the *institution manager* role.

In order to assist those agents, two agents are added for specific tasks: the **Planner Agent**, to build the delivery plans that are needed in the *Confirmation Room*, and the **DB Agent**, which is devoted to the role-based access control of the internal Database.

4 A network of Carrel institutions

In the previous sections the Carrel system has been described as an institution that works alone, managing all the requests and offers coming from the hospitals. However a distributed system is needed in order to manage the allocation problem at an international level (one of the aims of our scheme).

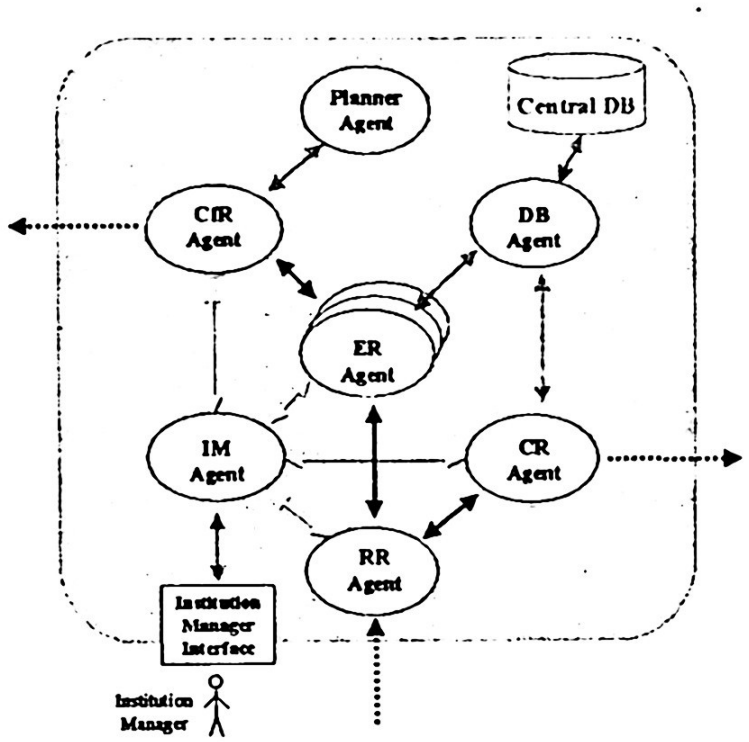

Fig. 8. The multi-agent architecture of a Carrel platform

To do so, we propose to create a federation of geographically-distributed Carrel platforms. Hospitals and Tissue banks register themselves to the "nearest" platform and interact as described in previous sections.

As a result, the search process is distributed through the platforms, exchanging information among themselves via their **DB Agents**. The process is the following:

- The **DB Agent** of a certain platform$_i$ receives a query, either from an *Organ Exchange Room*, a *Tissue Exchange Room* or the *Consultation Room*
- It accesses the local database.
- If the information is not available locally, then it sends part of the query to other **DB Agents** in other Carrel Platforms.
- All the diferences in terminology are solved at this point by the use of domain ontologies shared by all the platforms that define a common exchange format for the information.

All Carrel platforms are aware of the existence of the other platforms. The communication among agents on different platforms is acheived by the mechanism defined in the FIPA specification for communication among Agent platforms [8].

5 Conclusion

We have presented here an Agent-Mediated Electronic Institution for the distribution of organs and tissues for transplantation purposes. Our aim with this work is not only to

apply multi-agent technologies to model the organ and tissue allocation problem but we also have devoted part of our efforts in formalization, following the recommendations in [9] about the need of formal design methods when applying agents to the medical domain in order to ensure the *safety* and *soundness* of the resulting system. In our case we have chosen a formalism called ISLANDER [7], based on the dialogical framework idea, to get an accurate description of the interactions among the agents. By means of such formalism we have been able to design a system that combines the strengths of agents with the adventages of formal specifications.

As far as we know, there are very few references in the literature about the use of agents in the transplant domain. [15] and [12] describe single agents to solve specific tasks needed for this domain (respectively, a receiver selection algorithm based on multi-criteria decision techniques and a planner for transport routes between hospitals for organ delivery). [11] proposes a multi-agent system architecture to coordinate all the hospital members involved in a transplant. [1] also proposes a static hierarchical agent architecture for the organ allocation problem, but no formalism is used in the development of the architecture, and no mechanism is presented to make the architecture adaptive to changes in policies or regulations. For an extended discussion see [17].

Future work aims to extend the methodology to introduce explicit representations of norms to allow agents to reason about the norms. The agents will be able to make better choices in special circumstances. We will follow Dignum's work in [6], incorporating the abstract norms and values of real organizations' statutes and formally connecting them with their implementation in the electronic institution's procedures and protocols. In doing so we will get a full description of an institution, from the abstract (higher) level to the implementation (lower) one.

Acknowledgements

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Using the Internet to influence public knowledge and attitudes about health

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Abstract. The increasing availability of evidence-based medical information on the Internet has great potential to empower patients and health professionals and equip them for better decision-making, improving health outcomes. However, previous research has only evaluated the quality and accessibility of online information rather than the impact this information is having on the user. With these new technologies, are we actually empowering patients and professionals, improving their knowledge and changing their attitudes in a way that will impact on their behaviour? This paper presents the results of a pilot study investigating whether information within a medical digital library changes user knowledge and attitudes. The study had positive results with significant changes recorded. We conclude that digital libraries have the potential to change knowledge and attitudes of a range of users, but we need to evaluate this impact to inform digital library design in order to maximise the impact on users.

1 Introduction

Recent years have seen an explosion in the amount of information available to patients. There has been a shift from the patient as a recipient of health care to a consumer of health care, taking an active role in management of their health. The balance of power is shifting, but it requires skill on the clinician's part to adapt to patient preferences. They have to know when to hand over decision-making, when to share it and when to take a paternalistic approach [1]. Patients may now present to their clinician armed with reams of information and as a result, preconceived ideas about their health. Technology has facilitated this shift, with the Internet providing access for patients to information previously unavailable to them. As well as considering usability issues of ehealth technologies it is important to consider the impact of the information they provide to patients on their knowledge and attitudes. Are patients applying the information in an appropriate manner that will assist them and their clinician in managing their health? Or is the information retrieved by patients inaccurate, or simply misunderstood?

Medical digital libraries can have an important role in empowering health professionals and patients, providing timely access to quality-controlled information. To quote the title of a paper by Brice and Gray "Knowledge is the enemy of disease" [2]. However, it is important to target information appropriately to users so that the infor-

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mation accessed by them has the maximum impact on their knowledge, attitudes, and subsequent behaviour. As already suggested, health professionals have to adapt to patient preferences providing them with an appropriate depth of information. Patient empowerment should not be about providing patients with the information that will lead them to agree with their clinician, rather enabling them to make an informed decision with their health professional.

Lancaster identifies a current gap in the level of information held in NHS Direct Online, (online health information for the UK public found at: http://www.nhsdirect.nhs.uk) and that held in the National electronic Library for Health (NeLH) http://www.nelh.nhs.uk. The UK National Health Service provides both of these resources, the former aimed at patients and the public and the latter at health professionals. Lancaster suggests that the gap between these is too great and that they should provide access to a range of levels of information, indicating the level of difficulty for each resource within them and allow users to select information according to their current needs and preferences [3].

This paper shows that health information websites and digital libraries can have an impact on user knowledge and attitude and in future, become key vehicles for delivering information to empower patients, in order to allow them actively participate in the decision making process. Specifically it:

- Presents results demonstrating changes in the knowledge and attitudes of users to antimicrobial prescribing following use of a health information website/digital library
- Investigates the application of this research to evaluating the impact of digital libraries on user behaviour.

The rest of the paper is organised as follows. Section 2 discusses previous and current research around consumer health information seeking behaviour, the role of digital libraries as health information providers. Section 3 describes the health information website used in the research and provides a background to the area of antimicrobial resistance. Section 4 presents the results of the research so far and Section 5 discusses these results in the context of developing a methodology for evaluating the impact of medical digital libraries on user knowledge, attitudes and behaviour. Section 6 provides a conclusion and summarises the next steps of the research.

2. Background to the research

Consumers' use of the Internet for health information

The Internet has long been a source of health and medical information for consumers and use is growing. Pew Internet and American Life reported in November 2000 that 52 million Americans were using the internet to find health information whilst in May 2002 this had risen to 72 million [4]. Many studies have investigated consumer use of the Internet for health and medical information. Reasons for going online to find this information vary [4-8]:

- For themselves or someone they know
- For a second opinion or more information than they got from their doctor
- To see if they need to visit the doctor
- To find information to take with them to a consultation

But are they actually taking this information to their doctor? And are patients empowered by this information to take a more active role in decision-making with their doctor? The Health on the Net Foundation (HON) surveyed almost 3000 internet users using websites approved by HON. They found that 63% of users discuss information found on the internet with their doctor [8]. The Pew Internet Survey indicated that only a third of those surveyed would check Internet information with their doctor [4]. The difference here may be partly cultural as the HON survey was web-based whilst the Pew Internet survey was telephone based and only undertaken in the US.

Information seeking habits may vary between patient groups. For example, in contrast to the image of the information hungry consumer portrayed by these surveys, a study of cancer patients in the UK suggested that these patients would actively avoid seeking more information than provided by their doctor for fear of losing hope of recovery [9]. In addition they had faith in their doctor that he/she had told them all they needed to know and were concerned about using what they perceived to be limited information resources when others may be more in need. This latter concern is addressed by the ubiquitous nature of the Internet providing unlimited access to one information resource. However, this study, although small and not with a statistically representative sample, highlights the importance of not assuming that patients want all the information that ever existed on a particular topic. Henwood et al also found that some patients do not want to seek out information and are happy to trust their doctor, leaving decisions to them and avoiding the responsibility of managing their own health [10]. Given these conflicting behaviours it is becoming increasingly important for clinicians to adapt to patient preferences.

An important question to be asked of health information on the world wide web (WWW) is "What is the point of it?". The ultimate aim of providing any non-biased, authoritative health information aimed at consumers has to be to improve health outcomes, reducing the burden on the current health system. The NHS would not be investing millions of pounds into provision of digital information via a variety of platforms if it did not see some long-term benefit to the healthcare system from the education of consumers [11]. At Stanford University, Bob Fogg is pioneering an area of research he has called "captology" (the role of computers as persuasive technologies). He discusses the methods used by businesses and government to persuade consumers to change their attitudes or behaviour in specific ways [12]. Online health information providers have similar aims. They are attempting to provide the public with specific information in order to influence public knowledge, attitudes and subsequent behaviour. It is clear from the research discussed above that consumers are using the Internet to retrieve health information. But what is the impact of online health information on consumers and how can we evaluate it? Are we actually empowering people by providing this information? We know people are looking for information, but we also need to know how and where they are looking. The next section discusses current research into consumer online information seeking behaviour.

Consumer health information seeking behaviour

The Pew Internet and American Life survey reports extensively on consumers search techniques on the internet [4]. Eighty six percent of consumers didn't ask anyone advice about which sites to use and of those that did most asked family or friends rather than health professionals or librarians. Most just go to general search engine sites rather than medical information portals. The typical American consumer will visit an average of 2-5 sites per visit and spend 30 minutes doing so. In their last search most were concerned with retrieving information quickly rather than recognising a trusted name or sponsor. A study in the British Medical Journal, using web logs to record the searching activity, supported the idea that consumers use search engines first in their search for medical information online [7]. This is in contrast to the HON survey which found that 70% of users will go to medical professional sites with the second most popular sites being not-for-profit organisations [8]. This difference reflects the variation between the groups surveyed suggesting that for HON users the need to ensure the authority of the information is greater than the need for a prompt answer. These findings suggest that appropriate meta tagging and submission to quality portals and promotion in the virtual world is more important to increase awareness of resources than promotion via health professionals in the "real" world.

It is the concern that most consumers are relying on their own judgments of quality when retrieving resources e.g. from search engines, that has prompted the development of portals like HON (http://www.hon.ch) and Organising Medical Networked Information (OMNI) (http://www.omni.ac.uk) where users have access to a database of medical Internet resources, safe in the knowledge that these resources have been given a seal of approval (each site has a checklist to assess the quality of resources) by the portal indicating the quality and currency of the resource. A more recent development in the UK is the National electronic Library for Health. Although aimed mainly at professionals this site is a gateway to quality appraised, evidence-based information to equip professionals and patients with knowledge on which to base healthcare decisions. (See http://www.nclh.nhs.uk/new_users.asp).

But what do consumers consider marks of quality? We have already discussed that sometimes speed or retrieval may be more important to consumers than authority [4]. Four key attributes cited by consumers as important are; the source, accuracy, authority and trustworthiness of the information [4, 7, 8]. Consumers are reassured when information is duplicated across different sites, they avoid sites that are too commercial, may leave if they cannot see a source or date, and if they don't understand the information they will look somewhere else but are less likely to ask their doctor [4, 5, 8].

Recognising the source, checking the date is often quickly and easily done by consumers. However, the key problem for a lay user assessing the quality of a resource comes with checking the accuracy. Cline et al comment that consumers may:

- Fail to recognise that key information is missing
- Fail to distinguish between bias and unbiased information
- Fail to distinguish between evidence-based and non-evidence-based claims
- Misunderstand health information intended for health professionals [6]

All this research provides a useful insight into consumer behaviour when searching for health information online. It is important to look at what factors they take into account so that health information websites and digital libraries can make their sites more appealing to consumers and maximize their impact on users. However, what consumers say and what they do are probably not the same. Few consumers refer to checking the date and source of medical information when reporting their online behaviour [4]. To gain a wider picture of consumer behaviour we need to know what they actually do when online. The next section discusses the value of web log analysis in evaluating actual user behaviour.

Recording user online behaviour

Web log analysis provides information about the path a user takes through a website [13]. We can find general patterns in use e.g. most commonly visited pages, search terms used, time spent on a page etc. We can also employ a technique known as microanalysis, analysing use of the library by a small number of individual users. This provides a clearer picture of individual user behaviour when in the library, rather than general trends [14].

But what is the benefit of this analysis? Apart from informing general site restructuring and design [13] patterns of user behaviour can be used to personalise websites, providing the user with an individual experience when the visit the site. In the health information/digital library domain personalisation of medical information has been shown to improve patient satisfaction with information [15], reduce hospital admission of asthma patients [16], and to improve physician knowledge and attitudes about Chlamydia screening [17]. However, it is not so simple that any form of personalisation or tailoring will increase the impact of a resource or intervention on the user [18]. In addition many of these personalisation techniques rely on previously obtained knowledge about the user e.g. questionnaires to find out about user demographics, current knowledge and attitudes and personal preferences.

An alternative or indeed complimentary method of personalisation uses web logs and data mining techniques. This has been pioneered in ecommerce, the personalisation of Amazon being one such example [12]. Here the user is presented with products they have recently purchased or viewed and products they may like to purchase. The identification of potential purchases is based on activity by other users who have similar online behavioural characteristics. Patterns of user online behaviour are recorded over time and may be linked with collected personal data. When a new user visits the site their initial behaviour can be matched to that of previous users, and the site can be tailored accordingly. This technique can be particularly useful for attracting new visitors to register with a site, making them feel that the site is appropriate to their needs [19].

So personalisation could be a useful tool to aid digital libraries in empowering users. But we need to measure the impact of such techniques on user knowledge and attitude to evaluate their effectiveness. The next section discusses the context of the project, outlines the public health concern that is antimicrobial resistance and describes the methods used in the initial evaluation.

3. Initial evaluation methods

Information about antimicrobial resistance for the public

In his 2002 report "Getting ahead of the curve" the Chief Medical Officer identifies antimicrobial resistance as a key priority [20]. The report suggests that educating and informing the public is an essential component of any strategy for reducing the further development and spread of antimicrobial resistance, a view that is supported by previous influential reports [21, 22]. Research has shown that doctors believe patient expectations play a major role in inappropriate use of antibiotics [23-25].

Investigations into the impact of community-wide campaigns and videotapes about antimicrobial resistance, on prescribing patterns and patient expectations, have shown that they can reduce the expectation of antimicrobial prescribing [26, 27]. However, in spite of the increasing interest in providing health information over the Internet resulting in initiatives from Government organisations e.g. NHS Direct Online (http://www.nhsdirect.nhs.uk), commercial enterprises e.g. Netdoctor (http://www.netdoctor.co.uk) and non-profit organisations e.g. Health on the Net Foundation (http://www.hon.ch), and whilst some research, as discussed above, has attempted to discover how consumers search for and assess health information on the Internet little is known about the impact of this health information on knowledge and attitudes. A recent systematic review suggested that there was a paucity of evidence showing that consumer use of the Internet for health information has any effects on health outcomes [28]. We could not find any studies which investigated if the Internet could influence attitudes to antimicrobial prescribing.

The antimicrobial resistance website

The website was developed as an interface for the public to information held in the National electronic Library for Communicable Disease (NeLCD) http://www.nelcd.co.uk. The NeLCD is a specialist library of the UK National electronic Library for Health (NeLH) and provides a freely accessible, online, evidence-based, quality-tagged Internet portal to the best available evidence on prevention, treatment and investigation of communicable disease [29]. As indicated earlier in this paper, the education of the public about antimicrobial resistance is key in tackling this problem, therefore, although the NeLCD is aimed at health professionals it was considered important to provide an access point for the public to evidence-based information in this particular area of medicine.

The aim of the site is to "to inform the public of current evidence-based guidelines on antimicrobial prescribing and the issues surrounding those guidelines in an effort to reduce patient pressure on doctors and subsequently reduce inappropriate prescribing". The main content of the site is found in over 60 frequently asked questions, grouped into 22 categories. These FAQs provide short evidence-based answers, written by the NeLCD team, with links to the evidence and related questions on the site. Each FAQ is indexed using MeSH keywords to permit keyword searching. Each category is assigned a collection of relevant external resources, all catalogued using

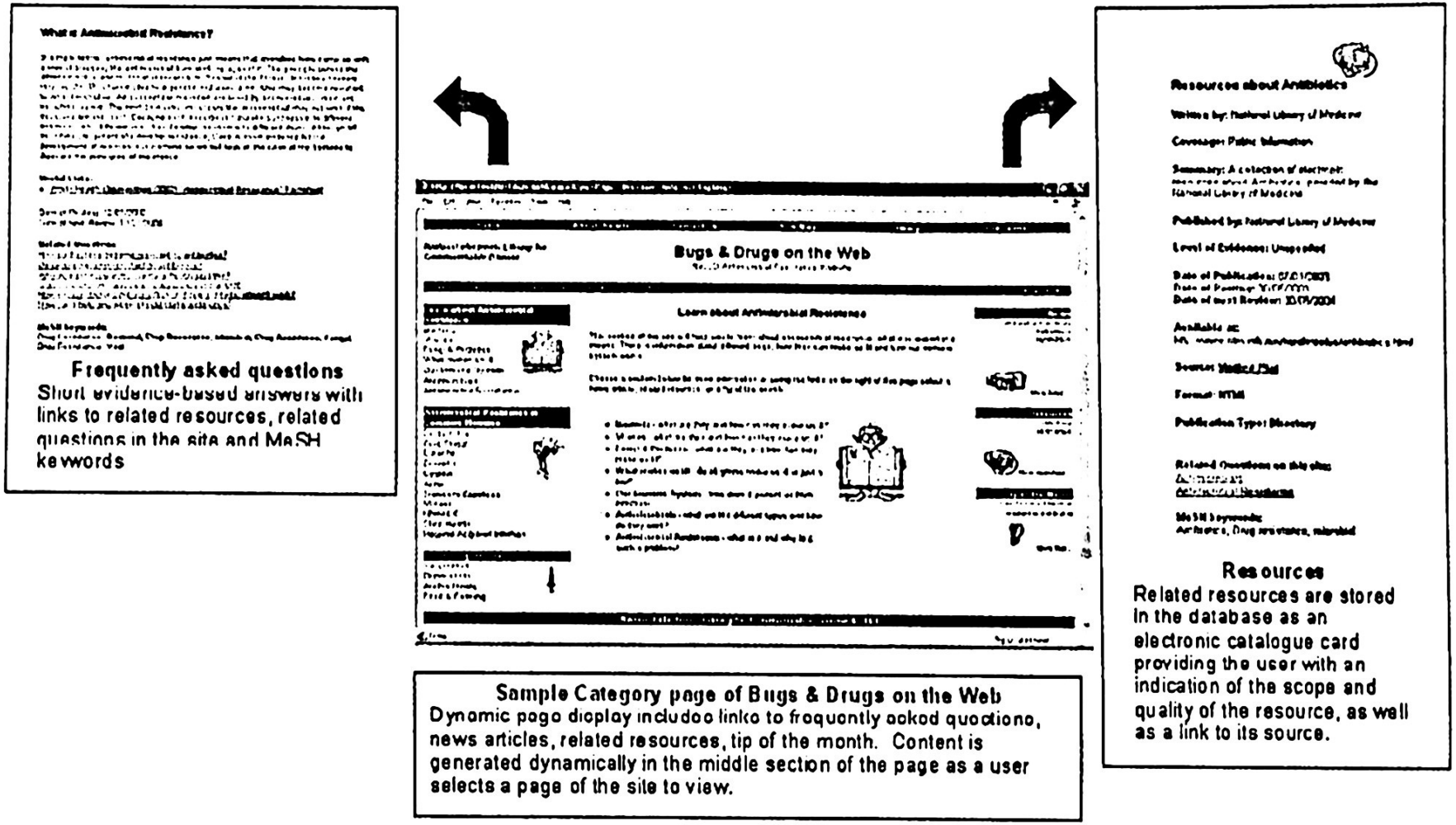

Fig. 1. Sample page of the Antimicrobial Resistance website with explanations of different areas of content

the NeLCD electronic catalogue card based on Dublin Core. A short summary of the resource is provided to indicate the target audience, content and level of quality. In addition the site provides links to antimicrobial resistance stories in the news, linking to sites such as the BBC and Netdoctor. Figure 1 shows a sample page of the website and example questions and resources.

Pre and post questionnaire evaluation methods

As already discussed, there are various methods to investigate user behaviour and self-reported use of online health information. However, there has been little, if any, investigation into the impact of this information on user knowledge and attitude. We wanted to conduct an initial study to investigate this impact. As the use of pre and post questionnaires testing user knowledge and attitude proved a useful method in previous studies evaluating the effectiveness of other forms of medical information (e.g. video and print media) on changing public or professional knowledge and/or attitude [17, 26, 27, 30] we adopted this methodology for this study. Pre and post questionnaires were designed to evaluate:

- General knowledge about antibiotics
- Attitudes to the use of antibiotics in a common ear infection (acute otitis media)
- Whether age, gender, experience with the Internet or level of education had any influence on the impact of the site on user knowledge and attitude changes i.e. does the site appeal to or is it more accessible to specific groups?
- The relationship between knowledge and attitude changes, and the usability of the site were also investigated but are outside the scope of this paper and are reported elsewhere [31, 32]

An expert in communicable disease validated the questions. Both questionnaires contained the same seven true/false statements about antibiotics and the same six likert scale questions (1 strongly disagree to 5 strongly agree) about antibiotic use in acute otitis media. These questions are shown in the appendix. The post-use questionnaire also collected demographic information about users. Participants were asked to complete the pre-use questionnaire, then encouraged to freely browse the website for around 10 minutes and asked to complete the post-use questionnaire when they left the site.

4. Results

Setting of the Study

The study took place in the Science Museum, London as part of 'live science' in February half-term 2003. Two hundred and twenty seven museum visitors were recruited opportunistically and of these 177 completed both questionnaires for which the results are discussed below. The study population recruited closely matched the Science Museum visitor statistics in gender, age, and highest level of education [33]. Results

were analysed and tested for statistical significance using an appropriate statistical test (paired t-test, McNemar's test or Fisher's Exact). The results are discussed below comparing changes in knowledge and attitude between different demographic groups. The seven true/false statements evaluating knowledge were marked by giving a score of one for each correct answer. A "don't know" answer was counted as incorrect. The six likert scale questions were on a scale of 1 (strongly disagree) to 5 (strongly agree) and these rankings were used as scores. When there was no ranking by the user they were left out of the analysis for that specific question, so the sample size was reduced accordingly.

Changes in knowledge and attitude

Overall there were significant improvements in knowledge ($p<0.05$) and a decreased expectation of antibiotics for acute otitis media ($p<0.001$). Differences between gender, age groups, education groups and confidence using the web are reported below.

Gender

There were almost equal numbers of both genders taking part in the study, with 86 males (49%) and 91 females (51%). Both genders significantly increased their knowledge scores after using the site and significantly changed their attitude ranks for all but one of the attitude statements. However, whilst females scored slightly, but not significantly, higher both before and after using the site than the males on the knowledge questions (an average score before using the site of 4.42 compared to 4.22 and 5.03 compared to 4.8 after using the site), there was no significant difference between the knowledge changes of each group ($p=0.9$). There were also no significant differences between the proportions of males and females agreeing or disagreeing with the statements in question two.

Age

Dividing users into age groups allows us to see if the site impacts different groups in different ways. For example, do children learn from the site as much as, or more than adults? Or is the site tailored more to adults? Do different age groups come with different levels of knowledge and attitudes? Are the age groups that are more likely to be parents more likely to expect antibiotics for AOM?

Table 1. Changes in knowledge scores by age. (N= number of participants, Pre= mean score before using site, Post= mean score after using site, Change= mean change in score, p= statistical significance of change using paired t-test)

	< 18	18-24	25-34	35-44	45-54	55-64	65-74
N	29 (16%)	17 (10%)	45 (25%)	44 (25%)	24 (14%)	10 (6%)	8 (4%)
Pre	3.48	4.35	4.36	4.49	4.96	4.44	4.2
Post	4.17	4.47	4.93	5.4	5.16	5.33	4.2
Change	+ 0.69	+ 0.12	+ 0.58	+ 0.91	+ 0.2	+ 0.89	0
p	**0.02**	0.39	**0.004**	**<0.001**	0.18	**0.005**	N/a

There were significant increases in knowledge scores after using the site for four of the six age groups: under 18, 25 to 34, 35-44 and 55-64. Table 1 shows these changes and figure 2 shows the changes in pre and post scores of the different age groups.

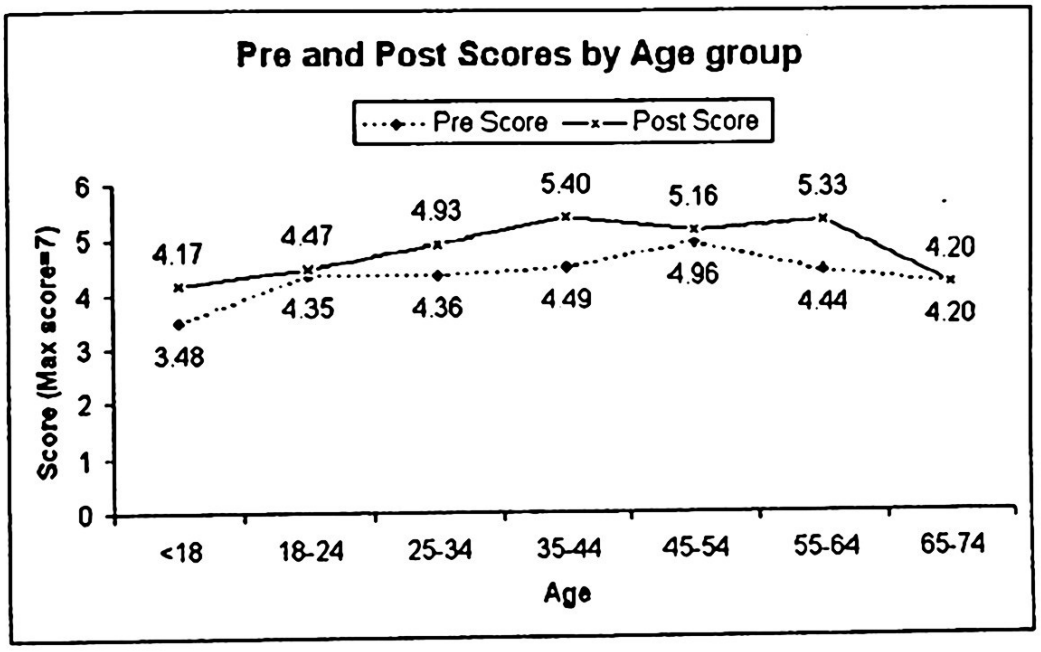

Fig. 2. Pre and post scores of different age groups.

There is variation across groups both before and after using the site. However, the noteworthy differences between groups were as follows:

- Between the total scores of the under 18 group and all other ages before using the site (p values: 18 to 24 =0.03, 25 to 34 =0.01, 35-44 = 0.006, 45-54 <0.001, 55-64 =0.03)
- Between the total scores of the under 18 group and the 25 to 34 group (p =0.03), the 35 to 44 group (p<0.001), the 45 to 54 group (p=0.02), and the 55 to 64 group (p=0.01) after using the site

For the attitude statements the only group to show no significant change in attitude to any of the statements was the 18 to 24 group. The 35 to 44 group showed significant changes in attitude to all but one of the statements. Those in the under 18 group, the 25 to 34, 35 to 44 and 55 to 64 groups were less likely to expect antibiotics for acute otitis media after using the site than before.

Education

The issue of whether level of education of users is related to the impact the site has on their knowledge and attitudes can help to indicate the suitability of the site for different groups. The use of antibiotics in acute otitis media is an area where the evidence-base is not clear and the limitations of current evidence is indicated on the website.

The level of knowledge of different education groups before and after the site and changes in their expectations of receiving antibiotics for AOM will help to indicate whether the information on the site is too basic or too detailed.

All groups showed significant increases in knowledge except the group with PhDs. The sample size of this group was too small (n=6) to allow it to be compared with the other groups. Figure 3 shows the pre and post scores of each group with the corresponding p value.

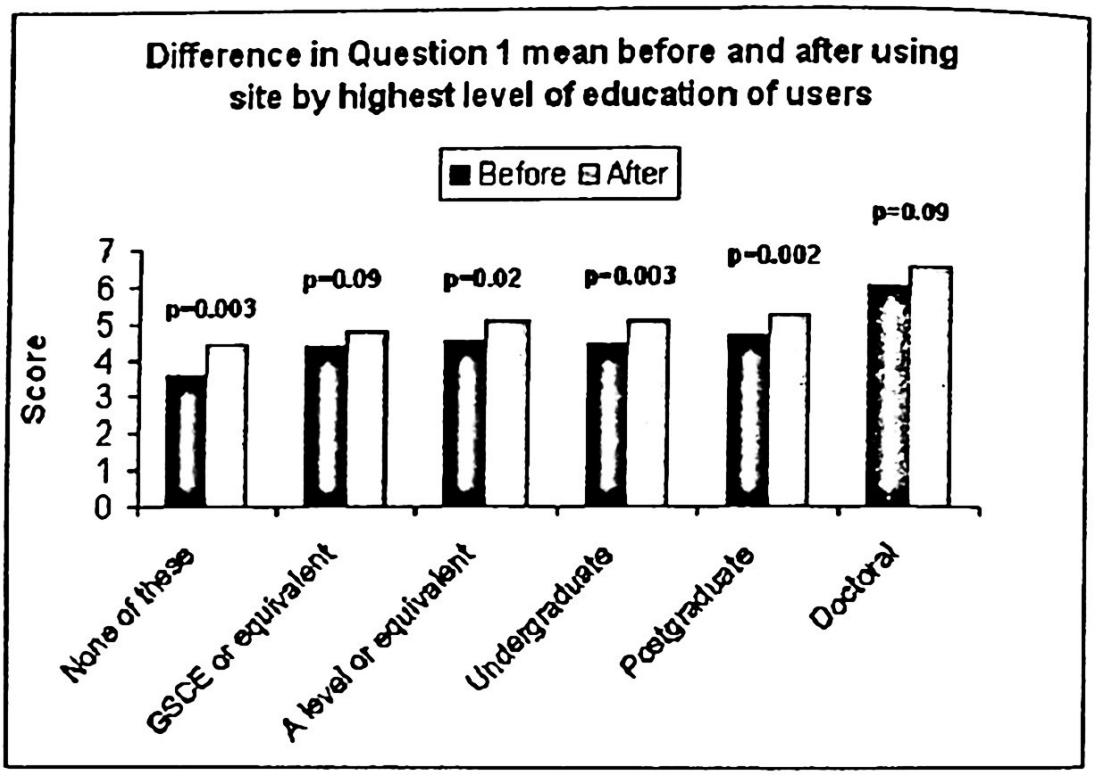

Fig. 3. Changes in knowledge scores by education group

The only significant differences in scores between groups (excluding the doctoral group because of the small sample) were:

- Between the "none of these" group and the GCSE group (p=0.02), the A level group (p=0.004), the undergraduate group (p=0.006), and the postgraduate group (p=0.002) before using the site.
- Between the "none of these" group and the A level group (p=0.03), the undergraduate group (p=0.02), and postgraduate group (p=0.01) after using the site

Only the postgraduate and doctoral groups saw no significant decrease in their expectation of receiving antibiotics for acute otitis media. The other groups were all less likely to expect antibiotics after using the site than before (p values: "none of these" =0.007, GCSE =0.05, A level =0.03, undergraduate =0.008)

Confidence using the Web

Although use of the web is increasing and more and more people are becoming confident web users, it is important to know that the site is not only impacting on those users that are confident with the technology but also on those who are not so familiar with it. Users were asked to rate their confidence using the web on a scale of one (not at all confident) to five (very confident). There was no significant difference in the proportions of users increasing their knowledge score between these five groups. Figure 4 shows the proportions of users in each group increasing and decreasing their score.

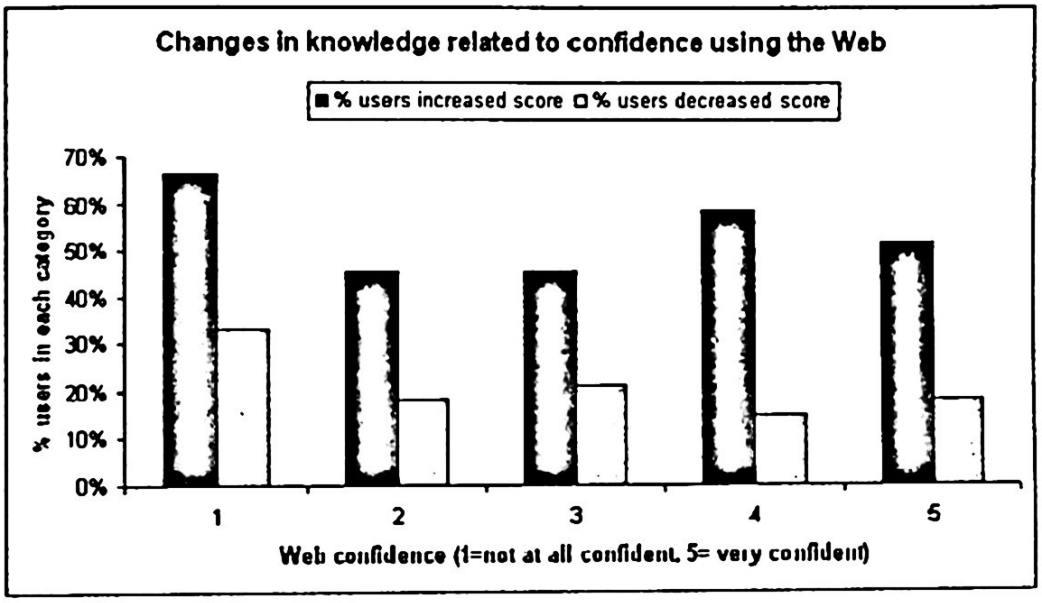

Fig. 4. Proportion of users increasing and decreasing their knowledge score by web confidence group

5. Discussion

These results suggest that for this group of users gender has no effect on knowledge and attitude either before using the site or after. Users under the age of eighteen can be expected to know less before and after using the site than the adults. While the site may not be particularly suitable for children, under 18 group did improve their scores significantly. The least impressionable age group was the 18 to 24 group. With respect to level of education, those without any of the qualifications listed had less knowledge before using the site than other groups. Although this group did improve their knowledge sufficiently for there to be no significant difference between them and the GCSE group after using the site. The fact that changes in knowledge were not related to confidence using the web could suggest that the site is easy to navigate for all levels of computer users. These results suggest that the impact of the site on user knowledge and attitudes is not dependent on demographic factors such as gender, age or level of education, or even confidence in using the technology.

But what does this mean for future evaluation of the NeLCD? This paper has presented a methodology that can be applied to evaluate the impact of the NeLCD on user knowledge and attitude. We have already discussed the value of analysing web logs in monitoring site usage and in personalising websites. If we can encourage users to register as "members" of the NeLCD and track their use of the library we can begin to collect more reliable data about user behaviour. By combining this with data collected at registration such as job title and grade, location, we can begin to build up a picture of how users behave within the library. We can evaluate user knowledge and attitude changes after using the site and compare this information to web logs, personal data about users and their perception of how the site has impacted on their work. This will help us to see how users best learn from the site and whether this varies between groups of professionals. Another important aspect of the NeLCD is the online community of communicable disease professionals. Will people who are more active in the community feel that they are learning more from the library or do they already come with a higher level of knowledge than other users? Does the site have more impact on those who are involved in every part of it or on those who focus on specific features e.g. the quality appraisals, the discussion fora etc. Can the NeLCD then be personalised for different groups of users or individuals, registered or not, and does this increase the impact of the library on users? And what about familiarity with the technology? Does that affect how much users learn from the site and why? Do those who come with less knowledge about a subject before using the site learn more than those with a greater knowledge?

Although not the primary aim of the library, there is a key role for the NeLCD in providing consumers with more in-depth, quality-appraised, evidence-based information than is currently easily available to them. We would like to investigate whether the public learns more from an NeLCD tailored for their use rather than a generic NeLCD for all users, what types of information public users want to access and how they expect to find this information within the NeLCD.

Conclusion

This paper has discussed the availability and user of consumer health information on the Internet and consumer online behaviour. It provides evidence that, in an initial study online health information was shown to change user knowledge and attitudes, but that these changes did not appear to be dependent on demographic factors or confidence using the Internet. The paper has discussed the potential of analysing web logs and personalising the library to increase the impact the NeLCD has on its users. It has presented a methodology that can now be further developed and applied to the NeLCD for evaluating the impact of the library on its users', their knowledge and attitudes and subsequent behaviour.

Future research will involve combining data from different sources in order to provide a better picture of user behaviour, preferences and learning. We hope to investigate the impact of the NeLCD on professionals and patients, comparing differences between these groups and within them. This paper presents the base on which this future research will be developed.

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Knowledge Management and Communities of Practice around Healthcare Digital Libraries

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Abstract.

The recent explosion of medical information available in digital libraries on the Internet provides users with overwhelming amount of medical knowledge. Although the number of patients seeking health related information online is steadily growing, the great potential of this revolutionary technology has not been fully exploited.
Professionals often cannot find information when and where they need it; members of public are unaware of varying quality of medical information and often seek health advice from unauthorized and misleading Web sites. In addition, little is known about the real impact of medical knowledge provision on clinical care.
Based on our experience with the development of real-world government medical digital libraries in the UK (NeLI and AR DL), we will discuss key issues around knowledge management, healthcare ontologies, quality approval and a new opportunity for online communities of practice around healthcare digital libraries.

1 Introduction

Recent technical advances resulting in a boom in medical informatics, that have enabled new ehealth-related activities, have got a common denominator: the Internet. As June Forkner-Dunn foresees: "the impact of the Internet has largely been unforeseen, and it may have a revolutionary role in retooling the trillion-dollar health care industry in the United States" [1]. However, the Internet can only play this essential role in healthcare if the knowledge provided over this powerful media is made accessible and delivered to the end-users – both healthcare professionals and members of public – in the right form to meets their needs. Therefore, the issues around the knowledge management in healthcare digital libraries and the impact on healthcare service and clinical practice are at the very centre of ehealth research.

In recent years, the ever-increasing amount of medical information available online and the increasing availability of the Internet at work as well as at home has significantly changed the way information are used by health care professionals and by general public. However, despite the desire of better informed patients to take an active role in the treatment process, and the need of professionals to keep improving their

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practice according to new results available in digital libraries on the Internet, the reality does not fulfil the expectations.

This paper will outline a number of technical, social and medical issues around medical digital libraries and knowledge management in medicine based on our long-term experience with the development of two government DL projects: National electronic Library of Infection (NeLI), formerly National electronic Library for Communicable Disease (NeLCD), and the Antimicrobial Resistance Digital Library (AR DL), both developed at the City eHealth Research Centre, City University.

The paper is organized as follows. Section 2 will discuss motivations for our research in greater detail, section 3 brings brief description of both DL projects: NeLI and AR DL. Section 4 is devoted to knowledge management issues in digital libraries, such as quality of the provided information, medical ontologies and the search issues. Section 5 discusses creation of online communities of practice around digital libraries as a new phenomenon enabled by the Internet and the impact of Internet and knowledge provision on public. Intelligent agents, used in the development of NeLI to serve the needs of the knowledge, are discussed in section 6. In section 7 we outline related research and section 8 concludes.

2. Motivations

The impact of new healthcare technologies

The introduction of technology into the health services brings a number of major improvements and it is envisaged that the overall impact of ehealth on the quality of care will be significant, however, there are also new issues and problems that need to be addressed.
According to June Forkner-Dunn: "As a group, physicians use the Internet more than do many other sectors of the general adult population. However, physicians have not received sufficient information to convince them that they can provide higher-quality care by using the Internet; indeed, few studies have assessed the Internet's value for improving patients' medical self-management and health behaviour, as well as their clinical outcomes and relationships with health care practitioners. New etechnology formats introduced to the growing consumer movement will drive the next generation of self-care by allowing patients to manage their own health conveniently and proficiently". In this section, we outline the impact - potential pros and cons of ehealth technologies.

Advantages

Ehealth already has a major impact on organization structures, clinical decision-making and health care practise. In particular, there are number of new issues wide adoption of ehealth would bring:

- significant influence of the work patterns, such as tele-health
- constant availability of the up-to-date knowledge and evidence
- instant dissemination of latest results and outbreak alert notification
- encouragement of best practice deployment and evidence-based care adoption
- potentially improved overall organization and delivery of care
- online professional communities and knowledge sharing
- online patient groups of those with the same conditions
- patient self-management using e-monitoring and empowered patient
- changed patient-physician relationship resulting in patient-centred decision making

However, the obstacles in current heath care settings slowing down or stopping an adoption of new technologies need to be identified, as these factors need to be clearly understood in order to be appropriately addressed in future research and policy definitions.

New problems:

In addition to the existing clearly positive impact allowing a better and higher quality care, there are new issues that need to be addressed in ehealth research. For example, they include issues such as:

1. Trust issue (trust and mistrust of the technology)
2. Security and confidentiality issues (EPR protection)
3. Implications of differential access to the Internet and different user abilities to use computer technology
4. The effect of "digital divide" and the impact on patient health and health care
5. Issues around the quality of information over the Internet
6. Standards – unification of coding and quality standards at national and international levels
7. The impact on the performance could be double-sided: e.g., "mail from patients further burdens overflowing physician schedules" etc.

The Role and Challenges of Digital Libraries

As discussed above, the Internet provides overwhelming amount of medical information. However, healthcare professionals and general public often cannot find the information they need when they need it and if they do the quality may be uncertain. Therefore, the knowledge provision, organization and delivery at the technological, medical and social levels are significantly changing the delivery of care and play a central role in empowering patients who are taking an active role in management of their health.

The role of traditional librarians has significantly changed, as shown at study of Adams and Blanford [2], demonstrating that a librarian acting as an information facilitator implemented within the community could adapt to and change practices according

to individual and group needs that was seen as empowering to both the community and the individual.

The key challenges of medical DL research we have been investigating on the real-world projects: NeLI and the AR DL span across a number of research areas: the quality of medical information, the search and user information seeking behaviour, issues around knowledge management, healthcare ontologies and the underlying technical services (such as agent-technologies in NeLI) implementing the service. Before we move on to these issues, we briefly introduce the aims of the two projects to set the scene for the following discussions.

3. National electronic Library of Infection: a Case Study

As mentioned above, our team has been developing two government medical digital library projects: NeLI and its part: the Antimicrobial resistance DL. These projects were used as ideal testbeds for our research into knowledge management, deploying agent-technologies in document management process and evaluation of the impact of these projects. Here, we briefly state the aims of these libraries:

NeLI, a specialist library of the NeLH, is an information gateway and a digital library providing the best available evidence-based knowledge, enhanced with medical quality tags to a wide spectrum of users: clinical experts, public health, general practitioners and general public. The top page is illustrated in Figure 1.

The Antimicrobial Resistance Digital Library, a subset of the NeLI, is providing information about antibiotics and prescribing to raise the awareness of these issues among members of public and to encourage prudent prescribing. The content of the library is organized in FAQs to answer common user questions and gives the links to more detailed resources, as illustrated in Figure 2.

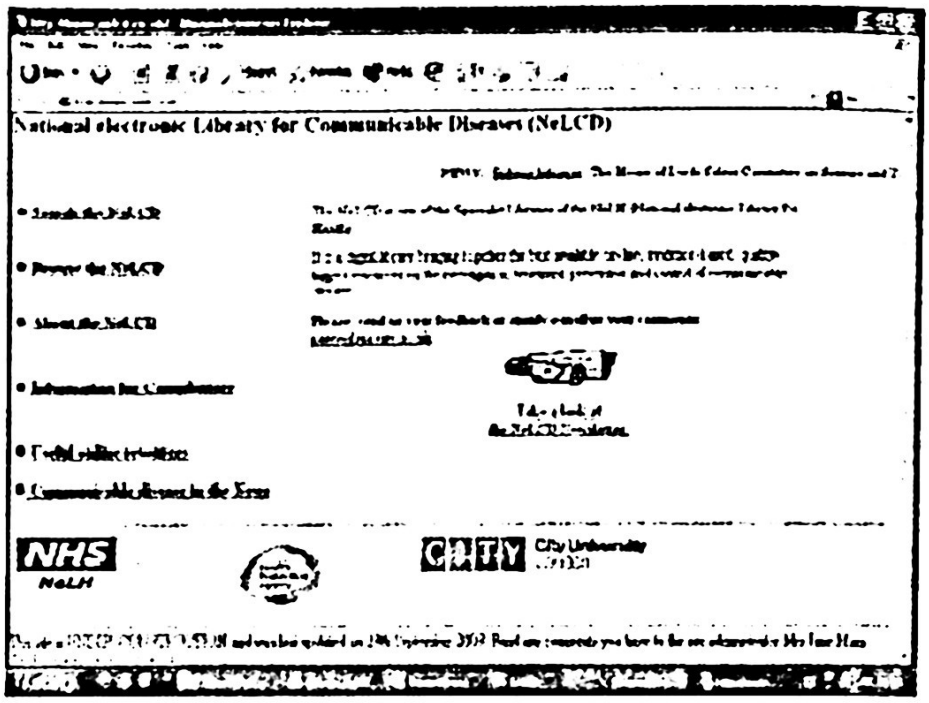

Fig. 1 National electronic Library for Infection

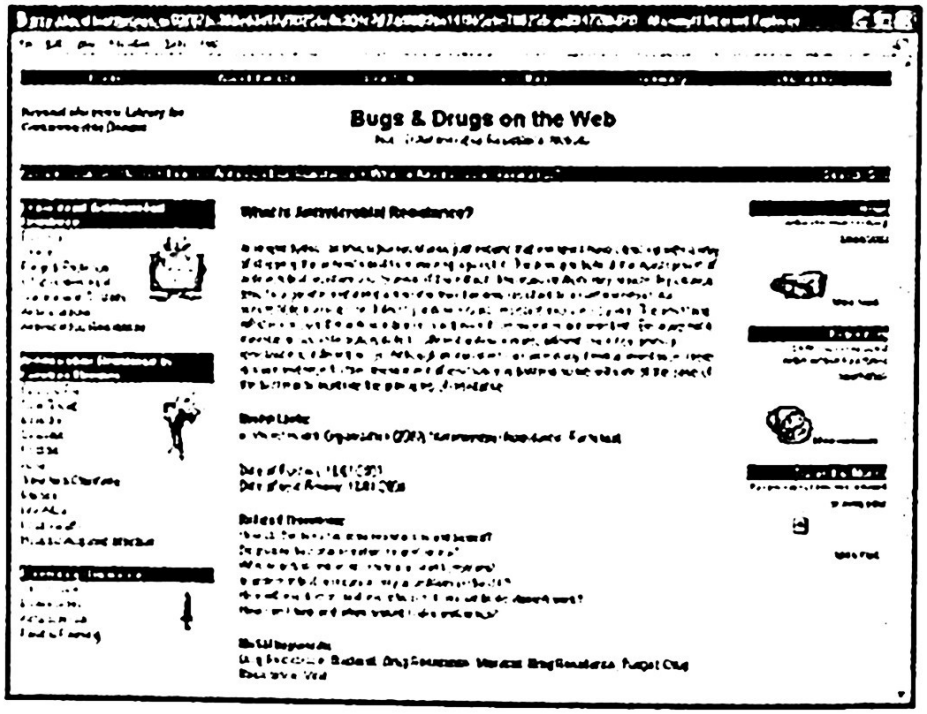

Fig. 2 The Antimicrobial Resistance Digital Library

4. Knowledge Management in Medicine

The knowledge management is a fundamental issue for the design of a digital library. Gray and Brice understand knowledge as the enemy of disease, as described in their recent study [3]. Understanding the problems around data representation – the nature of the data, data modelling concepts and user search behaviour - can ensure that required information will be retrieved in a way to meet users' expectations. In this section we will discuss a number of key issues around knowledge management with respect to the needs of NeLI and AR DL.

Quality Assurance in Healthcare

The problem of quality of health information is a very central one to a successful delivery of information to healthcare professionals and public [4]. The quality of information on the Internet significantly vary and providers and authors are often unknown or unspecified. This is the case of commercial, charity, private and sometimes even government digital libraries. This is of a particular issue for patients retrieving information from unreliable or bias Internet sites and burdening their GPs with obscure requirements or demanding contradicting or harming treatments.

Number of projects providing health information approval schemes, quality check lists and seals of approval offer only partial solutions – these include, National Institute for Clinical Excellence (http://www.nice.org.uk), HON portal (http://www.hon.ch), Organising Medical Networked Information (OMNI) http://www.omni.ac.uk are others. In the area of evidence-based medical quality appraisal the golden standard is the Cochrane collaboration [5]. However, research into public health information seeking behaviour by Eysenbach [6] showed that users often do not look at the "About us" page and seem uninterested in the provider of the web site they are retrieving information from, therefore, assuming that all health information on the Internet is correct.

The problem of information quality of science on Internet with respect the evaluation of the content from users' and librarians' points of view using interactive methods were investigated in great depth by Bargheer [7] who suggested a formal framework for evaluation of scientific material on the web.

In the UK, the National electronic library for Health (http://www.nelh.nhs.uk), of which the National electronic Library of Infection is a part of, is dealing with the issue of quality by making the level of evidence of all documents available and clearly including only evidence-based documents. Therefore, documents rather than Web sites are approved.

The details of the NeLI quality assurance process is based on Dublin Core meta-tags describing the online resources, the Reviewers Assessment giving a "bottom line" summary of the quality of the resources available for online discussion. The model of ongoing review process has been set up in collaboration with professionals around communicable disease in the UK. Full details of the quality-tagging and the appraisal process could be found in [8].

Healthcare Ontologies

Despite many ongoing national and international activities in Europe and the US, there is no common agreement on ontology, nor internationally agreed standards in health care adopted by national healthcare systems. There are number of coding standards, data representation standards and common legal and ethical recommendations. For example, there is no common internationally accepted clinical coding scheme – currently, several coding systems are being used by different organizations: MESH, CTLV3/SNOMED and ICD10. Common standards and their medical implementations, such as XML, Health Level 7 http://www.hl7.org/, UML, Z39.50 [9] (specifying an abstract information system with a rich set of facilities for searching, retrieving records, browsing term lists, etc) have not been widely implemented yet. This is not only a UK but an international issue.
Finally, a related knowledge representation project from NLM: the Unified Medical Language System (UMLS) develops and distributes multi-purpose, electronic "Knowledge Sources" and associated lexical programs to enhance systems focused on patient data, digital libraries, Web and bibliographic retrieval, natural language processing, and decision support. UMLS [10] includes a list of vocabularies in the UMLS Metathesaurus.

However, there is a need for harmonizing international standardization initiatives on one side, along with a development of ontology mapping tools allowing interoperability among digital libraries using different standards.

In NeLI, in addition to the MESH coding ontology [11], Dublin Core Metadata initiative (http://www.purl.org/DC) was adopted as it defines a list of fields characterizing an electronic document for cataloguing and search purposes. MESH is a standard coding system widely adopted in UK healthcare libraries and used for Pub Med indexing, while Dublin Core standard allows cross search with other NeLH Specialist Libraries and interoperability with other Internet initiatives, such as Open Archives (http://www.openarchives.org/). The meta-tagging was enhanced with fields to express the quality criteria, level of evidence and the Reviewers Assessment. Full details of these standards and their role in NeLI could be found in [8].

The search for health information

Understanding the issues of user search for health information on the Internet is essential for correct digital libraries design, graphical layout, navigation strategy and site user customisation. However, information seeking habits significantly vary among users and research results suggest that there is a great variety of user search patterns ranging from users seeking information to better understand their condition to patient rather avoiding to receive more information than their GP gave them. 86% of users did not ask anyone about which site to use and those who did preferred friends and family to health professionals and librarians [12]. Most people prefer general

search engines to medical Web portals, however, a study conducted by HON suggests that 70% of users prefer medical professional sites [13].

The key methods for investigating user search behaviour are qualitative and quantitative studies, the former using entry and exit questionnaires, interviews and online surveys; the latter typically investigating web logs that give an insight into quantitative information about each visit to the site, such as; number of hits, domain names, internet provider addresses, date and time of access, web server data, navigation strategy used, number of searches performed, downloads of documents etc. [14, 15]

For NeLI purposes, we have done a brief web log analysis of the pilot site for the period of January 2002 to June 2003. In particular use by hospital-based users was evaluated. Results indicate an increase in activity during the period and an increase in the number of hospital-based users. Hospital-based users were more likely to return to the site, spend more time on the site and to view more pages than other users. Surprisingly, the evaluation study revealed that users tend to browse the site more that search [16]. We are also in a process of collecting exit-questionnaire survey results, however, so far the number of responses is not statistically significant.

5. Online Communities of Practice and the Impact of Digital Libraries

Online communities of practice are one of the recent phenomena, enabled by the availability and affordability of the Internet, that can for-ever change the way healthcare professionals interact, learn and share knowledge. While traditional communities of practice have been widely studied [17], little is known about the key factors and the social impact of their online counterparts.

In particular, the impact of healthcare digital libraries on creation, evolution and sustainability of online communities of practice at national and international level is of very high importance due to the global outreach of medical events, such as infectious disease outbreaks. Recently, we have started investigating factors enabling people to interact effectively without having met face-to-face and discovering the barriers that slow down or prevent this interaction.

Additional research questions we are interested in include: finding out how online communication differs from face-to-face interaction and evaluation the impact of information graphical design and layout in this process. How the creation of online communities of practice around digital libraries change the knowledge update, problem sharing and results dissemination? What are the real-world social and practical obstacles slowing down this process?

The young community of practice we have been involved in creating about the National electronic Library of Infection is currently little more than an online extension

of the face-to-face community of professionals involved directly or indirectly in the project and we are investigating the key factors in this ongoing process, as described by Mani-Saada [18]. Initial research shows that the slow update of the community interaction is a result of the following factors: lack of time for busy NHS clinicians, insufficient quality-appraised content on the library and inappropriate technical support for advanced community interaction. These issues are currently being addressed.

The Impact of Health Information Provision

Providing quality medical knowledge through healthcare digital libraries available 24-by-7 to doctors and patients would be meaningless if there was no impact on public understanding, knowledge and attitude and if this ehealth resource would not improves clinical practice. While the DL evaluation research is focusing on search behaviour, accessibility issues, quality and navigation, little is known about the impact on user knowledge and attitude.

In our research, we have investigated, the usability, knowledge update and attitude change of health care professionals and general public using DLs. These factors we tested and evaluated on a study based on the Antimicrobial Resistance digital library, developed by our team (available soon at http://www.nelcd.co.uk) [19] Based on this very successful study, we are now investigating a general methodology for evaluation of the use of digital libraries, assessing knowledge update by public and change of processional practice based on information available on the Internet, in particular, on the National electronic Library for Communicable Disease (NeLI), http://www.nelcd.co.uk.

The aims of our ongoing research include the methodology for assessing the impact of digital libraries in healthcare and we seek answers to questions like: Does making the evidence available through digital libraries result in any difference in professional practice? Does the accessibility of information make the search for knowledge any easier and what are the key factors in the design of user-friendly elearning tools, from graphical and the knowledge provision point of view?

Communities of Practice and the Impact of Health Information Provision

Finally, the relationship between these two areas is currently being investigated. Firstly, we believe that healthcare digital libraries and knowledge management of medical information are pointless if they have no impact on online and face-to-face communities, the way health professionals work and interact, and on their clinical practice. On the other hand, communities of practice are rarely evolving spontaneously without a shared information need and a shared domain – there is a need for core shared resource, such as a digital library.

6. Technical Aspects – Intelligent Agents Support

The prototype of the NeLI library (http://www.nelcd.co.uk) has been built using CGI scripts to implement the basic search functionality. The top NeLH site could be found at http://www.nelh.nhs.uk.
Currently we are porting the system to Lotus Domino R5 platform and the new version should be later in 2003.

The prototype of the NeLI library was built around the 10 high-priority areas, identified in a national prioritisation exercise [20], and later populated with a core evidence-based documents with relevance to the infections diseases, syndromes and presentations. Documents in NeLCD are represented in XML (relevant DTD is defined for validation purposes). Common DTD across NeLH will allow extensive document exchange and cross-SL search performed by Information Agents. The separation of the content from style allows flexible manipulation with data, easy modifications of the display format, as well as object-based data representation suitable for data search and document exchange. The documents available at the prototype site are in the editorial process now and the Reviewers Assessments are being received.

Agent Support for Document Dataflow and the Quality Assessment

Lotus Domino built-in agents support is used for implementing the agent functionality supporting the document review process. The description of the agents in NeLI could be found in [21].

There are currently four basic agent concepts in the NeLI. First two, Intelligent Search Agents and Pro-active Alert Agents, are involved in the search process and user profiling and customisation. The later, Reactive Review Agents and Reactive Expiry Agents, are in change of various aspects of the library review process. The NeLI agents architecture is illustrated in **Fig. 1**. .

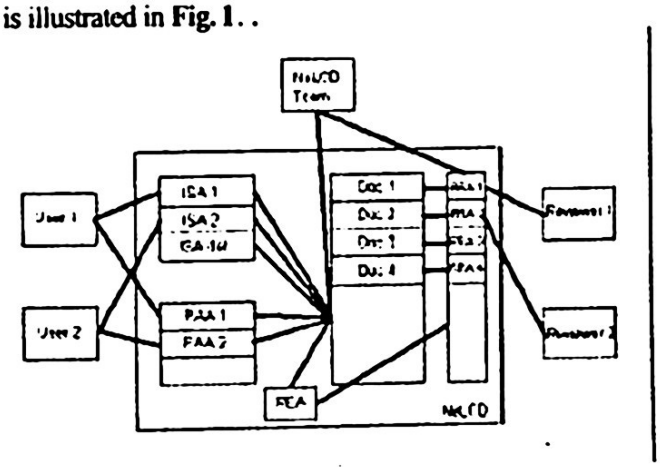

Fig. 1. Agents in NeLI

7. Related Work

While projects and research initiatives relevant to the issues discussed in this paper were described together with the approach or solution adopted in NeLI, in this section we give a brief overview of the key healthcare digital library projects and agent and interoperability standards in healthcare.

Healthcare Digital Libraries

NHS Direct Online http://www.nhsdirect.nhs.uk/ is a government-funded digital library providing basic healthcare information aiming at general public. This is a complementary service to the longer-running telephone service NHS Direct.

Prodigy (http://www.prodigy.nhs.uk/AboutProdigy/ initiative is a broad concept to support general practice in developing the quality of clinical practice in many ways.

Clinical Evidence project (http://www.clinicalevidence.com/) has identified existing clinical evidence and build a tool to access the knowledge to improve the clinicians' decision making. The outreach of NeLI is wider than clinical practise, the existing data sources are not homogeneous but heterogeneous, therefore, advances tools to accommodate the semantics are needed.

Cochrane Library http://www.cochrane.co.uk/ provides the gold standard in appraising clinical evidence. Following highly-critical evidence-based appraisal procedures, these guidelines provide the primary source of information for EB clinical diagnostics and treatment.

Autonomous Agents and Interoperability in Healthcare

Autonomous gents providing various functionality in health care applications have been an interesting area of research in recent years in academia and industry. For example, agent project by Honeywell is investigating applications of autonomous agents in elderly patients nursing [22], agentcities-funded (www.agentcities.net) healthcare project is looking at implementing MAS for negotiating patients visits to specialists according to his or her condition and physical location [23]. Agents-assisted recommendation for screening of cancer patients and other projects were investigated by Cancer Research Fund, UK [24]. However, the NeLCD seems to be the only project using agent technology in medical digital library.

As for the distributed communicate aspect of the library, there are a number related digital libraries providing a collection of cross-searchable documents in the Internet. The Z39.50 [25] standard specifies an abstract information system with a rich set of facilities for searching, retrieving records, browsing term lists, etc. At the server side, this abstract system is mapped onto the interface of whatever specific database management system is being used. The client application is unaware of the implementation details of the software hiding behind the network interface, and it can access any

type of database through the same, well-defined network protocol. On the client side, the abstract information system is mapped back onto an interface which can be tailored to the unique requirements of each user. This provides a well founded universal solution, conceptually similar to the one in NeLH, however, the NeLH is a proprietary database which does not aim to provide universality. The same is the case for the general SDLIP communication protocol [26].
A similar approach, looking at a tree hierarchical topology for communicating agents was investigated by Kostkova as the MAGNET Architecture [27].
Also, commercial Web publishing products, such as developed by Interwoven [28], do not provide the additional autonomous functionality required by the NeLH document quality review and appraisal process, as discussed in [29].
Finally, a related non-agent knowledge representation project from NLM: the Unified Medical Language System (UMLS) develops and distributes multi-purpose, electronic "Knowledge Sources" and associated lexical programs to enhance systems focused on patient data, digital libraries, Web and bibliographic retrieval, natural language processing, and decision support. UMLS [30] includes a list of vocabularies in the UMLS Metathesaurus.

8. Conclusion

In this paper we have outlines the technological advances enabling the recent growth in ehealth technologies, in particular, we highlighted the central role of the Internet and online digital libraries. Based on our experience with the development of National electronic Library of Infection and the Antimicrobial Resistance Digital Library, we have investigated the key issues around knowledge management, quality assurance, online communities of practice and the impact of medical information provision on end users.
These research results contributed to our understanding of the use of Internet ehealth digital libraries and the impact of online communication tools in healthcare that could subsequently improve the design of these systems.

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BanTeC, an image management software for corneal transplantation

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Abstract. The aim of this project was to develop a program called BanTeC (*BANco de TEjidos Corneales* – Corneal Tissue Bank). This software has been designed and developed to be used by the staff of the Tissue Bank, in the *Hospital de la Santa Creu i Sant Pau* (Barcelona, Spain). Its main objective is to provide a tool to manage all the information concerning the corneal tissues, as well as the application forms sent by other hospitals, since the Hospital is a tissue distributor at a national and an international level. This program should be considered as a support tool for CARREL.

1 Introduction

Until the date, almost all the management of the tissues of the Tissue Bank has been performed manually, using only paper support: no database nor computer tool was used to control electronic versions of the used documents and medical reports. All the information concerning a single piece of corneal tissue was then spread between folders containing hand-written evaluation reports, a computer connected to a specular microscope used to acquire and store image files, and fax tissue requests from other transplanting centres.

The main objective of the BanTeC project was then to create a computerised system to integrate and classify all the information and the documents used in the Hospital to manage all the donated and transplanted corneal tissues. The developed system carries out two important tasks: to make the control of the corneas much easier, integrating all the information into a single database system; and to create an case-based historical archive, that can be used to make statistics and studies in order to improve the quality of tissue processes. In short, BanTeC software aims to achieve the infor-

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matization of the Tissue Bank. All the stages of the development had been covered, from specification of the functionality needs of the system, the design of its architecture, the implementation of the different software components, to the total integration of the final solution in the real production environment. This is a first significant step towards the use of intelligent agents; these agents must be able to use the available information to mediate among hospitals to speed-up all the processes and support medical decisions. The design of the CARREL multi-agent system is presented in [3], [4] and [5]; this project is today being developed at the *Hospital de la Santa Creu i Sant Pau* and at the *Universitat Politècnica de Catalunya.*

2 Scenario

Firstly, it is very important to describe all the different steps of the life cycle of a cornea used for transplantation. Only if these phases are perfectly known, we shall be able to decide the functional requirements of the software application we want to specify. This section aims to give all the details of the real scenario of the Tissue Bank and enumerate each step and process that must be followed before and after corneal transplantation.

(a) EXTRACTION: when a patient dies in the hospital, he/she becomes a potential organ and tissue donor. If the hospital can get the family consent, the tissue bank doctors and the corresponding surgeon will then start the retrieval process of tissues. Concerning corneas, it is very important to act immediately, to avoid tissue damages after the death of the patient. It's then absolutely necessary to control the different time gaps between the death (asystole) and the beginning of the conservation process of the cornea tissue in a cold environment, since several processes have to take place: enucleation (extraction of the eyeball) and resection of the corneoscleral disc.

(b) DATA ANALYSIS (obtaining clinical data): once the corneal tissue is stored and preserved in the chamber (4° C), several groups of data have to be collected. These data concerns the cornea itself and the donor as well. They may give to the ophthalmologist all the necessary information in order to decide if the extracted tissue may be used for transplantation or not. Different kinds of tests must be done:

· Donor serology: several parameters are here necessary to evaluate an hypothetical transplantation: blood group, Rh, absence of antibodies against different viral diseases (mainly AIDS and Hepatitis B and C). A sample of the tissue is sent to the laboratory to be cultured to discard fungus or bacterial infections.
· Biomicroscopy: the tissue is observed using a split lamp that gives the doctor a macroscopic perspective of the analysed cornea in order to check that there is not any important damage nor any undesirable characteristic in it.
· Microscopy: a specular microscope is used to analyse the cornea; this device generates a string of images that allows the specialist to find the endothelial cell

count and its size and variation. The doctor can, in short, decide the quality of the extracted corneas.

(c) EVALUATION: using all the collected information in the previous step, the doctor of the Tissue Bank can generate a report to evaluate the cornea. This report must decide if the tissue is suitable for being used for transplantation and then implanted in a recipient or, otherwise, if it must be discarded.

· If the quality of the tissue is good enough and it can be used for transplantation, it can be preserved at 4°C for a week, waiting for a recipient to request it. The cornea may then be allocated and transplanted if such a recipient is compatible and matches some necessary parameters. After 7 days, the tissue is no longer valid and cannot be used anymore.
· If the cornea is not suitable for transplantation, it normally can be used for study or academic purposes.

(d) REQUEST: the Tissue Bank of the *Hospital de la Santa Creu i Sant Pau* is a national and international tissue distributor. Other hospitals send tissue requests using telephone and fax machines. These request must hold all the information about the destination hospital, the personal information and data of the recipient and any other relevant information concerning the need of a transplantation (diagnosis, data of the operation, ophthalmologist that is going to perform the transplantation and so on). If there is not urgent needs, the requests are fulfilled in chronological order (of course, a possible recipient must match some clinical parameters).

(e) ALLOCATION: once there is several available and valid cornea in refrigerator of the Tissue Bank and several unfulfilled tissue requests, the doctors of the Hospital de Sant Pau must try to allocate each cornea to the most appropriate recipient, according to compatibility rules. When a tissue is finally allocated to a request, the doctor of the Tissue Bank sends by fax the evaluation report to the destination hospital, where the surgeon that is going to perform the transplantation must accept the tissue. If so, the Tissue Bank must plan the transport of the piece and send also a bill reflecting its cost (procurement, preservation, quality control and distribution) to the destination hospital.

(f) CONTROL: when a hospital receives a cornea for transplantation from the Tissue Bank of the Hospital de Sant Pau, it undertakes to send back a information report after three weeks. That report must reflect the state of the transplantation: successful implant, eventual infections, primary rejection and so on.

(g) ARCHIVE: the Tissue Bank must always keep all the information and reports about extracted, distributed and transplanted cornea tissues. Even if a cornea is not suitable, all the documents concerning it must be stored. Only doing so, the Tissue Bank can eventually generate statistic reports about its activity, analyse them and use the results to improve the performance of its processes. Further-

more, all the generated information and images about corneas can be used with academic or study purposes.

3 Objectives

The used documents and reports, and the workflow processes described in the previous section are the main threads of the specification of the developed BanTeC application. The main objective of the project was to reflect and reproduce the scenario, described above, using essentially the same information that the Tissue Bank worked with. The aim of this section is to give a first approach of the most important requirements and features of the developed software system: which information is managed by the application, how it is shown, which operations can be performed with it and so on. The main functionalities of the system are listed next.

(a) Management (add/delete/edit) of all the information concerning donated corneas and tissues. That includes data about tissue registration (identification code), donor personal information (name, age, cause of death, other diagnosis), extraction data (exitus, enucleation and resection date and time, extractor ophthalmologist), donor blood group and Rh, donor serology results (HIV, HBV and HCV), bitmap images acquired using the specular microscope, microscopy (cellular density and size, variation rate, pachimetry) and biomicroscopy (eventual damages and/or structural injuries) results. Using all the previous information, the application must allow the doctor to validate (suitable for transplantation) / invalidate (not suitable for transplantation) the cornea.

(b) Management (add/delete/edit) of the information about received tissue requests. This information concerns destination hospital data (name, address, telephone and fax number, contact person), recipient personal data (name, age, blood group and RH, diagnosis, medical record) and any other relevant information about the request (date, transplantator ophthalmologist, planned date of the operation, urgent need and so on). The system allows the doctors of the Tissue Bank to allocate a valid cornea into a recipient waiting for it. When that operation is performed, the system generates automatically a bill that the Tissue Bank will send to the destination hospital.

(c) Management (add/delete/edit) of the control reports, generated three week after the transplantation. These reports contain the following data: date of the inform, doctor, success/rejection, eventual infection and text comments.

(d) Implementation of a case-based image archive (image bank): the system database stores all the images generated by the specular microscope in order to allow doctors to study and compare particular cases.

(e) The processes and operations that can be applied to each cornea in the system depends on its state, according to the norms and protocols of the *Hospital de la Santa Creu and Sant Pau.*

(f) The system is able to generate electronic and paper (prints) versions of each kind of document and report previously used by the Tissue Bank. The impact of the integration of the software application was then reduced, since BanTeC adapted the previous workflow of each cornea.

(g) Implementation of a graphic editor of biomicroscopy diagrams. This editor allows the evaluator to create, annotate and edit images to represent the observations made using the split lamp in order to illustrate text annotations and cornea description.

The BanTeC application design had another secondary objectives that must be mentioned as well. These objectives are non-functional requirements, but had to be satisfied in order to guarantee the success of the project.

(h) The graphic user interface (GUI) must be as easy to use as possible, since the end-users are not usually computer or informatics experts, but doctors. It is then essential to implement a user-friendly interface: only this way, the experts in medicine will find the application attractive and use it.

Going on with the same idea, BanTeC includes an integrated help system. The aim of it is to assist the user with the main operations. The way to achieve this objective is to use very detailed and step-by-step explanations, screen shots and contextual help.

4 Used technologies

The aim of this section is to justify all the technologies used to develop the BanTeC project. Next, a list of such technologies is presented.

(a) The first design decision was to use a *wintel* platform to use and develop the project. Such a decision has a lot to do with the user-friendly interface mentioned above, since almost every single user in the hospital is familiar with Microsoft Windows and the way the applications works.

(b) Microsoft Access 97 and Microsoft Jet 3.5 engine was used at database level, since the amount of data managed by the application (300-400 donors, recipients, transplantations a year) does not require a more sophisticated and more expensive database engine. Microsoft Access 97 is the most commonly used database in the *Hospital de Sant Pau* and it is installed in almost every computer running under Windows.

(c) DAO 3.5 (Data Access Objects) was the chosen data access technology, since its efficiency is optimised to use together with the Jet engine.

(d) Microsoft Visual Studio and Visual C++ were the used environment and programming language to carry BanTeC out. Visual Studio offers the MFC (Microsoft Foundation Classes) to the developer. The MFC include DAO derived classes and are suitable to create Windows desktop applications.

The corneal images are stored and displayed using the bitmap (BMP) format, since the specular microscope generates them this way. The main advantage of it is that any quality loss is avoided; no color is used in those images, so the used disk space is reduced.

5 Limitations and future work

As said in previous sections, the BanTeC main objective is to help the Tissue Bank doctors in the management of all the corneas information, but this software system does not take any decisions nor any responsibilities. The aim of the system is to reflect and integrate all the information previously introduced by the staff and the doctors of the Tissue Bank.

First, the application cannot decide if a cornea is suitable or not for transplantation; this decision corresponds only to the doctors or to the responsible of the Tissue Bank. BanTeC cannot decide when a cornea is no longer valid for transplantation either, after a week of preservation: if the doctor finds it appropriate, the cornea could be allocated into a recipient. Finally, the software application will not decide how to allocate available tissues (BanTeC will not match donors and recipients); the application will not decide the order the requests are fulfilled either. All these responsibilities concern the doctors exclusively: BanTeC only will reflect the information and the state of the corneas of the Bank but the application will not act in consequence.

The previous limitations suggest an obvious line of future work. The idea is to design a multi-agent intelligent system to assist the doctors in cornea allocation process: this system will need to match parameters from the donor and the recipient (ages, serologies, histocompatibility...) and the tissue itself (cellular density and size, period of preservation). Another different line of development is to extend the system to manage different kinds of organs and tissues, since the scenario is analogue and very similar to the corneas scenario described in this article. The aim of the CARREL project ([3], [4], [5]) is to create a virtual organization for the procurement of organs and tissues for transplantation purposes.

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Computer-Supported Situated Work: Considering the e-Health Domain

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Abstract. This article discusses the role and impact of upcoming technologies, most notably sophisticated mobile computing, for the support of skilled and situated human activities. To link this quite general discussion to the domain of e-Health, the article starts off by explaining how various activities in this domain have to be understood as skilled and situated and how they might be affected by future technological support. After giving an account of the characteristics of situated and collaborative activites the article briefly introduces three relevant proposals for Integrated Projects for the European Union's Sixth Framework Programme. All of these projects feature different e-Health application fields, including emergency response teams, the next-generation operation room, and long-term patient records. The remainder of the article is devoted to a number of research challenges that have to be met in order to realize the full potential of future technological support for these e-Health application fields.

1 Introduction

In the present article future technological support for skilled and situated human activities will be discussed as it is envisioned and developed in current and upcoming research projects in Europe and elsewhere. The prospective enhanced support rests on foreseeable innovations on both the hard- and software-level, including e. g. the general availability of large numbers of networked interoperable devices providing computing and communication services, as well as highly context-sensitive applications using sensory data and interaction histories to adapt their services to their users. In order to foster a joint understanding of this idea within the research community and support coordinated and consistent research activities the European Commission is promoting 'Ambient Intelligence' as a guiding concept. It signals the shift from isolated and singular computing devices that host a defined set of functionalities to a situation where large numbers of interconnected potentially small devices provide services by sharing resources such as bandwidth or displays and allowing for free roaming of applications. Evidently, this vision poses large numbers of research problems ranging from the development of new mobile devices, sensor integration, novel forms of interaction such as haptic or tangible interfaces, network protocols, algorithms for interpreting and reacting upon context-data to the social take-up

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process of these new technologies, security, privacy etc. The net benefit of such support consists in overcoming the de-facto separation of situated activites and conventional supportive information and communication technology (ICT). By providing all services through portable or even wearable devices and adequately integrating them as much as possible with skilled activities, research hopes to turn sometimes ackward technological crutches into true amplifiers of human competence.

Of course, application fields for such support of situated activities extend well beyond the domain of e-Health. Nonetheless, e-Health is a highly relevant field of application because of its diverse and sometimes extremely demanding requirements. Understood in a broad sense, e-Health comprises rather different domains of skilled human activity, ranging from surgical teams working in operating rooms, emergency response teams sometimes having to attend to an unknown number of unknown people in an unknown and hostile environment, laboratory personal, homecare services, etc. In most of these cases teams of highly trained specialists use complex technological equipment to collaborate in feature-rich situations under high time pressure and with very low or virtually no tolerance for error. Consequently, providing the right information and expertise at the right time and place without hampering the e-Health professionals in their primary task is as benefitial as it is difficult. For instance, adequate support has to meet very high standards of reliability, demand its user's attention only economically all the while ensuring awareness of crucial information and it has to provide reasonable fall-back procedures in case some functionality fails. Another e-Health aspect of technological support that is often overlooked is that more extensive and integrated forms of support might also entail health problems in terms of stress or ergonomic inadequacy.

In the following sections e-Health will not be addessed directly but as a highly interesting instance of a skilled and situated activity. The following section gives a more in-depth discussion of ICT-supported situated activities, including the central aspect of collaboration. In section 3 three project proposals will be presented that touch on e-Health aspects and that have or will be submitted to the EU's Sixth Framework Programme (FP6) with the involvement of the author. Finally, in section 4 some of the ongoing research questions that the author intends to work on in these projects are presented. In presenting this work, one of the intentions of this article is to raise awareness for these European research activities and create contacts with parties outside Europe that might be interested in becoming partners in future proposals or join existing projects later on for e. g. dissemination activities.

2 Computer-support for situated collaborative work

The characteristic feature of using mobile computer technology to support human work is that people can be supported in the very situation where they carry out their primary task. The great advantage of such support of situated activities is that it can take into account the situational context which defines to a certain

extent what the task is and what its relevant features are. For this reason, human experts often depend on being in the task situation for accomplishing the task. Hence, the full potential of mobile support for situated activities is realized when the professional can integrate it with his competence to act in the task situation. These benefits carry over to collaborative activities in a natural fashion, being amplified by the additional social context of collaboration. The characteristic feature of mobile computer support for collaborative work is that the individual collaborators can extend their powers beyond their respective task situations by establishing network connections between distributed collaborators. The real potential of this is on the one hand to enable an individual person to better communicate the contextual circumstances of his task situation to remote collaborators and on the other hand to make a distributed task situation more observable and assessable as a whole.

To put this in concrete terms, using mobile computer technologies can help a physician to communicate his concrete problem situation when consulting a remote expert and it can help the chief of an emergency response team to assess a complex emergency situation and monitor and coordinate his team on the basis of the information received from his team members. Of course, similar processes have long been practised using simple technologies such as telephones, radio or post. But computer support can enhance these processes vastly by providing rich contextual information through sensors and user monitoring, as well as effective information processing such as filtering of irrelevant information and aggregation of multiple information sources.

In order to realize this potential of mobile computer-supported collaborative work, three fields of research have to be addressed:

1. The structures and processes of collaborative settings (e.g. work groups, expert consultation, etc.) have to be investigated and the potential benefits as well as issues of mobile computer support have to be evaluated.
2. Means of support in terms of hardware and software have to be developed that realize the benefits while avoiding or at least allow controlling the associated problems.
3. A methodology for deploying mobile computer-support has to be developed that assists the necessary changes in work practice and associated problems such as acceptance.

To start with, there are many different types of collaboration and most often a given collaboration is also changing over time. Consequently, mobile computer support is faced with highly diversified and dynamic requirements that cannot be fully anticipated at design time. On the one hand, this requires research on the spectrum of collaboration types and the processes that change them. On the other hand, it requires enabling the workers themselves to adapt their systems to the particular requirements of the current collaborative situation (cp. section 4.1). Empowering end-users to substantially adapt the systems is a prerequisite for the systems to become effective tools for the ever changing specific situational context of individual expert activities as well as efficient participation in a dynamic network of collaborations.

Apart from domain specific differences, a number of more general features also distinguish different types of collaboration: they can be ad-hoc or pre-established but loose networks and they can be in the form of trained communities with a specific collaboration culture. The collaboration can be self-organized or centrally controlled and there can be forms in between such as fully or partially autonomous sub-groups (e.g. cross-organizational collaboration). Collaborative settings can have more or less internal structure with different roles such as surgeon, anaesthesiologist, nurse and remote expert.

A particularly interesting type of collaboration occurs in trained and well-established groups - or communities of practice [Wenger, 2001] - such as a fire brigade or surgical team. In these cases the collaborators have formed a social network and group culture that defines standard behaviour patterns and endows the group with coherence, reliability and identity, allowing the community members to engage in a trusted and highly efficient collaboration.

As is well know from research in computer-supported collaborative work, support systems must be able to cater to the diverse and dynamic requirements of these types of collaboration and their associated processes, or otherwise they will either not be used or severely damage the collaboration's efficiency. Because of the dynamics of situated activities this is the more true for mobile collaboration support.

In the case of communities of practice the process of setting up the community, integrating new members and dealing with leaving members is of particular importance: efficient behaviour patterns must be found and trained, suitable members for different roles must be identified and new members must be integrated into the collaboration culture. Because of the distributed nature of mobile collaboration this calls for appropriate support by the mobile collaboration system. Other collaboration processes that have to be supported include decision making, problem solving, knowledge sharing, finding suitable collaborators, and skill dissemination through demonstration (see section 4.2).

On the level of mobile technologies, several kinds of support are known that have to be adapted to mobile collaboration support, including:

1. System adaptability: To accommodate for the diversity and dynamics of requirements between groups, within groups, and over time. Support compatibility of individual and group requirements (e.g. rights, scopes, consistency checks, negotiation processes).
2. Roles: handling of rights, duties, etc.
3. Awareness for collaborators and the group's overall status (idle, under stress, etc.). To support this, mechanisms for e. g. problem and conflict detection and resolution are needed.
4. Control: Procedures for escalation, coordination, notification services.
5. Interaction history or collaboration memory:
   (a) evaluation and debriefing
   (b) identification and reuse of effective interaction patterns
   (c) sustainable group experience
6. Modes of interaction and interfaces.
7. Support to assess the impact of individual activities in collaboration systems.

3 Three FP6 Project Proposals with e-Health aspects

The following three sections give a short introduction to three project proposals that include some highly relevant e-Health aspects and that have been submitted to FP6 or will be so shortly. The author has participated actively in the preparation of these proposals.

3.1 wearIT@work

The project proposal for wearIT@work has been submitted to the 2nd Call of FP6 on October 15. Within wearIT@work a considerable number of major organizations from research and industry have defined a joint and integrated research and development process to turn wearable and mobile computing into a truly productive asset for professionals in all sorts of work areas. In particular, field studies and tests will be conducted with partners operating in the fields of surgery, emergency response, automobile production[1] and aircraft maintenance. The overarching aim is to shape technology in such a way as to make it a seamless everyday commodity for professionals, for example by integrating it with the clothing and by providing unobtrusive user interfaces. Using this wearable and mobile computing platform, context-sensitive information and communication services will be developed that provide access to relevant information at anytime and anywhere. In the context of e-Health, wearIT@work will address the interaction of surgeons with the multiple devices in an operating room, following the approach to replace or augment all of the devices' interfaces with a single interface that the surgeon can access and operate through wearable devices, e. g. a head-mounted display. The benefit of such an interface will be to unite and aggregate the large number of information sources and control interfaces in a single consistent one that poses a smaller cognitive load on the surgeon and allows for sophisticated awareness support of relevant information. Secondly, wearIT@work also addresses emergency response teams working in hostile environments, such as fire brigades. In this context, monitoring the team members' vital status and leading the team based on this information is a matter of life and death. Coordination of medical attention in potentially large-scale emergency situations is a second aspect.

3.2 AmbieLife

The AmbieLife proposal has likewise been submitted to the 2nd call of FP6. It is strongly rooted in the 'Ambient Intelligence' (cp. Sec. 1) vision and one of its contributions would be to develop an architecture for networks of interoperable devices that provide their services to the network and thus allow for a seamless configuration of services that the individual devices could not provide alone. Obviously, such a network architecture is a prerequisite for attaining a high level of both flexibility and service quality in heterogenous device networks,

[1] Compare [Morgan et al., 2002] for an interesting account of this application field.

such as in an operating room. The second and at least as important aspect of AmbieLife is the idea of the Personal Information Space as the place where people can store and organize all of their information and that they can access from everywhere using whatever devices their current environment has to offer. When talking about skilled and situated activities one key benefit of the Personal Information Space would be that it can retain past experience embedded in their situational context, making it easier to reactivate, reassess, extend and share such experiences that are at the heart of human expertise. Within AmbieLife the connection with e-Health will be established by investigating the use of Personal Information Spaces for patient records in a hospital setting. While bearing substantial benefits in terms of access to information and diagnosis this usage also comes with serious issues in terms of security and privacy.

3.3 Human Work

The Human Work project will be submitted to the 2nd call of the so-called 'Priority 7' field within FP6, closing on December 10. As opposed to the preceeding two projects this one is not primarily oriented toward research on information and communication technology but towards research in the humanities and social sciences, as is required in 'Priority 7'. The main focus of this project will be on investigating the changes in work processes as brought about by the use of new technologies. To this end particular attention will be paid to the tacit dimension [Polanyi, 1983, Polanyi, 1998] of competent human activities and how it relates to novel means of support. As explained above mobile computing technologies allow for integrating support narrowly with the supported activities. Accordingly, the most exiting potential of mobile computer support is not about bringing explicit information to users but is about amplifying existing competence by providing sophisticated tools that people can assimilate to their tacit skills. Secondly, Human Work will also address the health risks associated with using new technological support.

4 Pertinent Fields of Research

To realize the functionalities and associated benefits discussed in the preceeding sections a number of research problems have to be addressed and resolved that are not specific to the e-Health domain but nonetheless highly relevant to it. Research at Fraunhofer FIT does also include very e-Health specific work like navigation support for minimal invasive surgery. But in the following sections three examplatory research fields at Fraunhofer FIT will be discussed that are relevant to a number of application fields including e-Health.

4.1 Adaptation Processes

End-users want IT-systems to meet their requirements. Capturing these requirements and letting software-professionals implement them is a workable approach

only if the requirements can be identified and remain stable over time. As stated in the introduction, end-user requirements are increasingly diversified and changing and may even be difficult to specify at a given point in time. Going through conventional development cycles with software-professionals to keep up with evolving end-user requirements would be too slow, time-consuming and expensive. While end-users are generally neither skilled nor interested in adapting the systems they are using at the same level as software professionals, it is very desirable to empower users to adapt systems at a level of complexity that is appropriate to their individual skills and situation.

But adapting systems to users during usage does not necessarily require dedicated activities on the part of the user. Adaptive systems monitor their users' behaviour and other contextual properties, like the current task or situation, and use different approaches, notably from Artificial Intelligence, to automatically adapt themselves . One important approach to increase system adaptivity is to increase this contextual awareness by taking more contextual properties into account and to set up user models to better assess how the users' requirements relate to different contexts.

Nonetheless, the distinction between system adaptability and adaptivity is not so sharp in practice. Users may want to stay in control of how systems adapt themselves and might have to supply additional information or take certain decisions to support system adaptivity. Conversely, the system might try to preselect the pertinent adaptation options for a given context or choose an appropriate level of adaptation complexity for the current user and task at hand, thus enhancing adaptability through adaptivity [Klann et al., 2003, Oppermann, 1994]. The following two sections explain adaptivity and adaptability in some more detail.

Adaptivity The aim of adaptivity is to have systems that adapt themselves to the context of use with respect to their functionality, content selection, content presentation and user interactions. Systems displaying such adaptive behaviour with respect to the context of use are called context- or situation-aware.

One aspect of situation-awareness is related to properties of the user itself, like the level of qualification, current task or previous behaviour. Traditionally, these properties have been captured in user models, which have been processed to generate appropriate adaptive behaviour. Currently, situation-awareness is continuously augmented by taking more and more situational properties into account . In particular, various sensors are used to gather information on properties relating to the physical environment of the context of use, like the time of day, location, line of sight, level of noise, etc. Other situational properties of the context of use of a particular user relate to what may be called the social environment, being composed of other users, communicative and cooperative interactions, shared artefacts and common tasks. One example of such an adaptive system would be a tourist information system on a mobile computer that presents specific informations based on its users location, movement, profile of interests etc.

The basis for a successful and effective information and communication system is providing information and functionality that is relevant and at the right level of complexity with respect to the users changing needs. As these changing needs are largely related to the situational properties, relevance and appropriate complexity can be supported by system adaptivity, which is to say by automatic proactive selection and context-sensitive presentation of functionalities and contents.

The objective of adaptivity is to assist the users by proactively supplying what they actually need. This way, users are not distracted from their primary task by searching and selecting. A good quality of such adaptivity clearly depends on complete and accurate user- and context-models, as well as on correct conclusions derived from them.

At Fraunhofer FIT development of a Contextualization Framework is under way that will provide a modular architecture for acquiring sensory data and other contextual properties, interpreting and integrating this information and deriving appropriate context-aware system activities.

Adaptability The aim of adaptability is to empower end-users without or with limited programming skills to customize or tailor computer systems according to their individual, context- or situation-specific requirements.

Approaches to adaptability include:

1. End-user-friendly programming languages , see e. g. [Repenning et al., 2000]
2. Programming by example[2] respectively Programming by demonstration, see [Lieberman, 2001]
3. Component-based tailoring, see e. g. [Stiemerling et al., 1999]

By avoiding costly and time-consuming development cycles with software engineers whenever possible, such approaches allow for fast adaptations to dynamically changing requirements by letting the end-users put their domain specific expertise to the task of system customization. While currently still being in its infancy with simple adaptations like macros for word processors or e-mail filters, more sophisticated forms of adaptability should enable end-users to become the initiators of a coevolution between the systems they are using and their own requirements as defined by their tasks, level of expertise and current working context.

Work on adaptability has been consolidated over the last two years in the European FP5 project EUD-Net [EUD, 2003, Klann et al., 2004]. EUD stands for end-user development and has been promoted as a unifying term for the various adaptability approaches.

For the domain of e-Health the concept of adaptability or end-user development is highly significant because it empowers domain experts such as doctors

[2] Taken as a conscious activity and not as an accidental side-effect to usage, Programming by example constitutes a case of adaptability. But as it also requires system activity, namely deducing some function from the users behaviour, it may also be considered a case of adaptivity.

and nurses to use their expertise to modify the ICT systems they are using more quickly and accurately than would be possible with the help of professional developers.

4.2 Knowledge processes

When dealing with human competence traditional approaches in ICT often tried to formalize expert knowledge and provide this explicit information to users in a decontextualized way. Problems with ageing and maintenance of such explicit knowledge as well as with interpreting and transposing it to changed problem situations has started research on alternative ways of making expert knowledge available. One such approach is to use profiling techniques to evaluate and describe the skills and expertise that a given member of a community has and to use these expertise profiles to bring members seeking and members providing expertise together for communication and collaboration. At Fraunhofer FIT a modular ExpertFinder framework has been developed that allows for plugging in different profiling and matching algorithms.

4.3 Design and Deployment Processes

Challenging the conventional view of 'design-before-use', new approaches try to establish 'design-during-use' [Dittrich et al., 2002], leading to a process that can be termed 'evolutionary application development' [Morch, 2002]. These approaches are means to handle the dynamics of requirements. One particular difficult and important aspect concerning the heterogeneity of requirements arises because of cultural differences in the user community, both on the professional and ethnical level. Consequently, empirical ethnographical studies are an important means to identify and understand the diversity of requirements and they are a prerequiste for developing systems that are equally usable across cultural boundaries and in multi-cultural teams.

5 Conclusion

The present article has discussed the relevance of future computer-supported situated activities for the domain of e-Health. It has given an account of some of the associated research challenges and of how these are being addressed in current EU research project proposals. It would be a very positive effect if this article can spark an interest in these research activities, maybe make some of them a little more transpartent and eventually support research collaboration with partners from outside Europe in the context of FP6 or elsewhere.

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e-Tools: The use of Assistive Technologies to enhance disabled and senior citizens' autonomy.

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Abstract. In this paper we present our preliminary ideas about the integration of several technologies to build specific *e*-tools for the disabled and for the new generation of senior citizens. '*e*-Tools' stands for *Embedded Tools*, as we aim to embed intelligent assistive devices in homes and other facilities, creating ambient intelligence environments to give support to patients and caregivers. In particular, we aim to explore the benefits of the concept of *situated intelligence* to build intelligent artefacts that will enhance the autonomy of the target group during their daily life. We present here a multi-level architecture and our preliminary research on navigation schemes for a robotic wheelchair.

1 INTRODUCTION

Nowadays it is clear the growing importance of the role that Artificial Intelligence (AI) – specially Knowledge-Based Systems (KBS) – is playing in medicine to support medical practitioners in making decisions under uncertainty (see [13]). Also, in medical scenarios where many individuals are involved in a decision-making process or when their decisions and actions have to be coordinated, *Agent-Based Technology* (software systems composed of intelligent *Software Agents*) is getting an increasing role to a) model the processes, and b) model the decision making processes (see [12]). However most of the current applications are centred in the information dimension of health care management (see §3.2).

Robotics is another field with growing applications. Robots are moving away from factories into environments such as private homes, in order to assist people in (very simple) daily routines. However, there are fewer projects investigating the use of autonomous robots technology for disabled and elderly people. Much of this work is devoted to the creation of electric wheelchairs that can autonomously navigate through an environment (just as a robot would do) [26]. Nevertheless,

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there are also some promising uses of robotics' technology (sensors, artificial vision) to create other services such as patient position tracking.

Ambient intelligence (AmI) builds on three recent technologies: *Ubiquitous or Wearable Computing*, *Ubiquitous Communication* and *Intelligent User Interfaces*. *Ubiquitous Computing* means integration of microprocessors into everyday objects like furniture, clothing, white goods, toys, etc. *Ubiquitous Communication* enables these objects to communicate with each other and the user by means of *ad-hoc* and wireless networking. Finally an *Intelligent User Interface* enables the inhabitants of the AmI environment to control and interact with the environment in a natural (voice, gestures) and personalised (preferences, context) way [10].

The senior citizens represent a fast growing proportion of the population in Europe and other developed areas [5]. This paper presents some of our ideas about the use of all these technologies, integrating them into everyday environments and rendering access to services and applications through easy-to-use interfaces, especially designed for the disabled and the senior citizens. The use and creation of new technologies for the disabled is crucial, as for this group of people assistance is not merely a matter of *doing* the same things more quickly or in a simpler way with the aid of an *e*-tool. For them it is a matter of *being able* to perform those tasks independently and, maybe, to learn how to perform new tasks in order to enhance their own autonomy.

The rest of this paper is organised as follows. In §2.1 we introduce the problem of disability and give some figures of its impact on society. Then in §2.2 we will discuss the interaction problem of senior and disabled people with technological devices. In §2.3 we address the issues of safety and soundness that are mandatory in systems integrating various technologies in a single platform. In §3 we address the possible uses of assistive technologies. Afterwards, in §4 we will introduce the *e*-Tools architecture and an intelligent robotic wheelchair as an example including most of our ideas. Finally, in §5, we make some reflections about the future of this technology.

2 DISABILITY AND THE SENIOR CITIZENS

2.1 Ageing and disability

The ageing of the population today is without parallel in the history of humanity. Increases in the proportions of older persons (60 or older) are being accompanied by declines in the proportions of the young (under age 15). Nowadays, the number of persons aged 60 years or older is estimated to be 629 million[8]. By the middle of the century, one fifth of older persons will be 80 years or older [16].

The increasing number of people affected by chronic diseases is a direct consequence of the ageing of the population. Chronic illnesses, such as heart disease, cancer and mental disorders, are fast becoming the world's leading causes of death and disability, including the developing world. Two examples of highly

[8] According to the Second World Assembly on Ageing Madrid, Spain 8 -12 April 2002

invalidating diseases requiring medical assistance and/or institutional care are represented by *Alzheimer's disease* and *stroke.*

Alzheimer's disease (AD) is the principal cause of dementia in the elderly, affecting about 15 million people worldwide. The earliest symptom is usually an insidious impairment of memory. As the disease progresses, there is increasing impairment of language and other cognitive functions. Last stages of the disease use to lead to an institutionalisation in some kind of facility specialized to treat such cases. But this solution not only has a high cost, but also is harmful for the patient, that is placed in a unknown environment with unknown people.

Stroke is the most disabling chronic condition. Its effects impact on virtually all functions: gross and fine motor ability, ambulation, capacity to carry out basic and instrumental activities of daily living, mood, speech, perception and cognition. Stroke represents a heterogeneous category of illness that describes brain injury, usually sudden (e.g. haemorrhages, vasospasms, thrombosis). Therefore, in each case the retraining and adaptation process to neurological handicaps depend on the nature of the underlying anatomic abnormality and not on the cause of such abnormality. Stroke may have a devastating impact of patients' lives.

In both developed and developing countries, chronic diseases are significant and costly causes of disability and reduced quality of life. An older person's independence is threatened when physical or mental disabilities make it difficult to carry out the basic activities of daily living such as bathing, eating, using the toilet and walking across the room, as well as shopping and meal preparation. One or more diseases can be involved in causing disability; at the same time, a single illness can produce a high degree of disability. Therefore, disabled people are a very heterogeneous group, comprising a wide spectrum of function. This ranges from mild impairment and/or disability to moderate to severe limitations. However, the concept of disability itself is not always precise and quantifiable. [9]

A related concept is the one of health environmental integration (HEI). [22] This concept has been expanded recently: originally it was presented as a framework to study how humans and machines interact and complement each other along the ICIDH-2. Now-a-days, AT therapeutics are directed at both the person and the environment. The objective is to enhance HEI by using devices to neutralize impairments. By neutralizing impairment, there is an expansion of people's potential to enter into, to perform major activities within, and to fully participate according to the structure of the surrounding physical and social environments.

2.2 The interaction of disabled people with technology

In the analysis, design and final creation of disabled-oriented devices, it is mandatory to keep in mind the interface problem, either because of a severe mental

[9] To facilitate agreement about the concept of disability, the World Health Organization (WHO) has developed the *International Classification of Impairment, Disabilities, and Handicaps (ICIDH-2)* and the *International Classification of Functioning, Disability and Health (ICF).*

or mobility dysfunction or the usual complex relationship among elder people and new technologies [20]. The Rehabilitation Engineering Research Center on Technology Evaluation and Transfer (RERC-TET) has focused on consumer-identified needs and preferences regarding several categories of assistive technologies. According to the classification of Batavia and Hammer [2], 11 criteria have been identified that disabled patients consider important: among others, *Effectiveness*, *Reliability* and, mainly, *Operability* – the extent to which the device is easy to use, is adaptable and flexible.

Fig. 1. An example of modern electric-powered wheelchairs.

The extreme difficulty with which persons with severe disabilities have been taught to manoeuvre a power wheelchair is an example of difficult interaction with AT: 9 to 10% of patients who receive power wheelchair training find it extremely difficult or impossible to use the wheelchair for activities of daily living; 40% of patients reported difficult or impossible steering and manoeuvring tasks; 85% of clinicians reported that a number of patients lack the required motor skills, strength, or visual acuity. Nearly half of patients unable to control a power wheelchair by conventional methods would benefit from an automated navigation system. These results indicate a need, not for more innovation in steering interfaces, but for entirely new technologies for supervised autonomous navigation [11].

2.3 Safety and Soundness

Even though the domain of application is restricted to a quasi-structured, *situated environment* where the most important landmarks will remain stable, *unexpected* changes may arise; therefore, the system needs to solve these unforeseen situations without entering in malfunctioning states. This implies that these systems need to exhibit an intelligent goal-oriented behaviour and yet still be responsive to changes in their circumstances.

However, as observed by Fox & Das [12], the use of heuristics or rules of thumb to solve problems seems unlikely to inspire confidence. In this domain the safety of users imposes bigger restrictions and the systems must be extensively tested – possibly off-line – to ensure effectiveness and performance of the devices. Therefore, *safety* should be one of the main concerns in the design of disabled-oriented devices. One possible option is to add a safety management layer in those systems. Likewise, the creation of safety plans is mandatory. That is a set of procedures and criteria that specify *what* the system is supossed to do when, but it deals specifically with hazardous circumstances and events [12].

3 ASSISTIVE TECHNOLOGIES

Assistive technology devices can be very useful to provide supportive services for individuals who require assistance with the tasks of daily living. Their use can be not only applied to people with cognitive impairment caused by aging factors but it can be extended to any disabled and handicapped people[10], in order to ensure an acceptable level of autonomy. By proposing *substitutes for* (or rather *extensions to*) nursing homes (i.e. Assisted Care Facilities), such assistive devices will help to reduce the patient's dependency (even from the psychological point of view) specially regarding the activity of daily life and improving his/her quality of life. Such supportive services are also helpful to the caregivers of those patients. In the patient's home environment, technology may aid non-professional carers (relatives, friends) in their efforts, contributing to lengthen the time spent by disabled and elderly individuals in their own home and to postpone the need for institutionalisation. In the hospital environment, such technologies may lead to a reduction of expenses, as increased autonomy of patients would lead to reduced nursing costs, and to a better use of the time and expertise of qualified nursing personnel.

3.1 Issues to be solved

Services targeted to disabled people should be capable of solving the following problems:

- *Monitoring problems*: the creation of devices that can track several signals from sensors placed in the patient and autonomously decide if the patient is in a safe condition or there is something abnormal that recommends to call for assistance (an alarm in the case of a Care Facility, an automatic phone call with an synthetic voice in the case of the patient's home).
- *Mobility problems*: The creation of devices (power wheelchairs) that are easily driven by people with mental and physical dysfunctions, and that are capable of autonomously taking decisions about *where* and *how* to go with the limited, even noisy inputs from the user and from the environment.

[10] From now on, we will use terms such as *patient* or *user* to refer not only to people with cognitive impairment caused by ageing factors but to the disabled and handicapped people.

- *Cognitive problems*: the creation of devices that support declining cognitive skills, including reminders, task instruction, and methods to reduce cognitive effort. A good example is the (quite frustrating) situation where the patient is able to *Remember what but not where* it is located. This is one of the most thrilling problems to be solved, as it requires a combination of technologies (e.g. a set of devices monitoring the user actions and linked with sensors and positioning systems installed in the room, all them interacting through wireless communications).
- *Human factors*: interfaces that meet senior citizen's needs and capabilities – motor, sensory and cognitive (see §3.2).
- *Decision-making problems*: reasoning systems that respond to situations and the elder's needs by interacting with devices in his normal environment, interacting with the elder, or contacting caregivers.

3.2 Integrating technologies to create intelligent assistive devices

There are several technologies that are useful to provide supportive services for physically or mentally disabled people.

Autonomous Agents *Autonomous intelligent agents* are capable of understanding their environment and of independently determining and reasoning how to use their own resources in order to reach a desired goal [25]. Such agents can be either physical (robots) or software components.

Autonomous Robots are physical agents that perform tasks in the real world autonomously. They differ from classical and industrial robots in that they do not have a fixed sequence of actions previously programmed but a set of possible actions that are chosen to be performed depending on given goals or/and information about the environment.

In the case of robots, *autonomy* is often related to *mobility*, and thus, the main task performed by autonomous mobile robots is considered to be navigation. Different techniques are applied to solve navigation problems depending on the different features of the environment such as its nature (indoors, outdoors, underwater or even planetary), the information available (map known or unknown, changes traceable or not) and the level of control over it (remains stable or is highly dynamic, landmarks can/cannot be added).

A robot interacts with the environment through its actuators and sensors; therefore, navigation techniques also depend on the sensors a robot is equipped with: a) laser, ultrasonic (sonar) and infrared sensors, to measure distances; b) pressure switches and bumpers, to detect collisions; c) wheel encoders and Global Positioning Systems (GPS), to compute location; and d) Vision systems, to recognize landmarks and targets.

Nevertheless, planning and positioning are two key aspects that must always be solved in any autonomous navigation problem. However, although many research efforts have been undertaken in this direction (see [14] for an overview), few of them have focused so far on disabled or elderly people [15].

Software intelligent agents are entities that interact with a *virtual* environment, obtaining information and exchanging it with other agents. Their reasoning capabilities allow them to do complex tasks such as allocating resources, coordinating the action of heterogeneous systems, or integrating information from different sources.

Most of the actual agent-based technologies in medicine could be classified, following [21], as a) *Patient centred information management*, b) *Cooperative patient management*, c) *Patient monitoring and diagnosis*, and d) *Remote care delivery*. However, all these applications are centred in the information dimension of the health care management. Until now, in the case of senior citizens or elderly people, applications of software agents have been directed towards the integration in society of this population subset via the use of virtual communities, trying to make Internet technology accessible to them (e.g. [3]).

The use of this agent-based technology could be easily conceived to help solve other problems that could help to enhance the quality of life of some people. An example is given by cognitive problems such as where the patient placed some item (the *Remember what but not where* issue). In restricted environments such as a house or a hospital, a software agent may help to trace the location of the desired object by keeping track of the *usual* places where this object should be or of the last time it was used and/or placed.

Another important area of application is safety management of technologies applied to health care. Software Agents' *proactiveness* could be used to perform an active safety management layer by the introduction of *guardian agents*, as in [12], that in a proactive way look for possible hazards and anticipate an answer or send an alert signal to the manager. For example, an intelligent wheelchair must never obey an order asking it to drive the user to the stairs nor to allow the composition of a plan to do that. However, it may override other conditions if the manager asks for it or in the case of an emergency – i.e. the agent should be able to recognise an emergency state – or to ask for help in the case of an impasse. To do this, it is necessary to build safety plans and to be able to reason about them.

Machine learning and other AI techniques In addition to Artificial Intelligence (AI) techniques that are used in the Autonomous Agents area, assistive technologies may also take advantage of other AI techniques. These techniques can be applied to face both monitoring and mobility problems originated by elderly or disabled people. Think about the problem of recognising some impasse situations, or even emergency situations where disabled people are completely lost in their everyday environment. There is also the possibility to learn some new tasks or behaviours to enhance the autonomy and good performance of disabled people moving within a particular environment.

All these situations can be solved through some AI techniques such as planning, knowledge acquisition and machine learning tasks. All these tasks can be implemented following several AI approaches, but taking into account the highly advanced technological framework envisioned for the immediate future where

ambient intelligence will provide the sensorial systems with large amounts of data and experiences in several forms, Case-Based Reasoning (CBR) seems to be a very promising approach, as it helps in learning new experiences, anticipating problems [18], re-planning, adapting old plans to new situations, and recovering or repairing a plan that might fail at execution time.

Affective Computing Traditionally, technology has been oriented towards supporting, improving or extending human capabilities in physical and "intellectual" (reasoning) tasks, disregarding the affective aspects of human cognition and interactions. This trend has started to change in recent years and a new field, generally known as *affective computing* [17], has emerged, building artefacts that can have (one or several) capabilities, such as recognising, expressing, responding to, facilitating, influencing, and in some sense "having" emotions. Research in this area has been very active in the last years, and numerous models and applications have been developed (see [6, 7] for a selection of representative papers).

The potential benefits of integrating elements of affective computing into assistive technology for disabled and senior citizens are wide-ranging, and can be seen from two perspectives:

Improving the emotional state of the user These users are more prone to experience negative feelings such as loneliness, anxiety and frustration, and (mild or severe) affective disorders, given the increased difficulty they have to carry out daily activities, and the physical and social isolation they often suffer. Assistive technology that effectively *cares* for these users should also be able to recognize and monitor their affective states, respond appropriately to them, and try to elicit positive reactions and feelings from the users.

Using emotions as cognitive aids Recent findings in psychology and the neurosciences have evidenced the fundamental role that emotions play in other aspects of human cognition, even in tasks traditionally considered as being the sole product of reasoning, such as memory (see e.g. [19]) or decision-making [8]. Therefore assistive technology should take into account that some aspects of emotions captured by bio-sensors can be used to influence and facilitate other cognitive tasks by means of user tailored interfaces.

Emotions often act as a memory biases that can reduce cognitive overload (e.g., people tend to remember better situations and events experienced under a similar mood). These affective "markers" could be added to memory aid systems to make recall processes more efficient. Another major problem that can be present in disabled and senior patients is the lack of a good reason or motivation to decide between alternative courses of action. As pointed out by [8], emotions play a major role as value systems that make us prefer one alternative to the rest. In the context of assistive technology, emotions could help to support decision-making processes by a) recalling or making the user aware of

the emotional implications of different decisions, and b) endowing assistive artefacts with internal motivational and emotional systems to allow them to make (simple) decisions autonomously.

Wireless devices *Wireless technologies* have created a revolution not only in technological achievement but also in social behaviours. The evolution in communication channels (to send and receive the maximum information with the minimum bandwidth use) has also come along with the increased availability of computational power inside small devices (PDA's, laptops, last-generation mobile phones).

Wireless links are usually based either on infrared or microwaves technologies. We will focus on microwave technologies, as infrared based links a) require direct visibility between transmitter and receiver, and b) transmission speeds are not very high. There are basically three different technologies for microwave based wireless communications: Wi-Fi, GSM/GPRS and Bluetooth. Currently *Wi-Fi* offers the best performance regarding coverage and speed. However, it presents a high power consumption. *GPRS* yields a low bandwidth and it is owned by mobile phone operators. *Bluetooth* is still under research, but it presents an adequate bandwidth and low power consumption. All these technologies allow the creation of many applications and services accessible through small, portable devices, easily carried by people from one place to another, and are the basis of some of the solutions proposed in the following sections to connect patients and caregivers with their environment.

4 THE *e*-Tools ARCHITECTURE

The scenario depicted in this section applies almost all the solutions presented in previous sections and it is based on a daily problem. Many disabled people of all ages base their mobility in the use of a power wheelchair. Usually those are driven using a mouse or joystick that allows the chair to navigate. However some disabled people experience considerable difficulties when driving a power wheelchair. Common manoeuvres are not at all easy (e.g. going out from a room). When the steering commands are not sufficiently accurate (due to spasticity, paresis or tremor in the upper limbs), a collision can result. And there is a group of target users that is unable to even use their hands. For these groups the solution is to provide them *Robotic Wheelchairs* with some reasoning capabilities that allow the Wheelchair to navigate in an area such as the patient's home or a hospital. The idea consists on the installation, on top of the hardware of a electric-powered chair, of a reasoning module that assists the user in the navigation. Most of the times the navigation is completely assumed by the reasoning module. [11]

For people who still can walk there are other alternatives. One of them are the so-called *Assistive Robotic Walkers*. These devices can be seen as passive

[11] Yanco elaborated a complete survey of this kind of assistive robotic wheelchairs [26].

robots that can steer their joints, but require a human to move them. Wasson *et al* [24] have been working in the development of these kind of personal mobility aids. Exactly which capabilities the walker exhibits at any time depend on the will and abilities of the user.

We will use as example the robotic wheelchair scenario, as the wheelchair has to show complete autonomy in tasks such as path planning, and be able to locate itself on an environment. Although we are thinking of a controlled situation in a quite well-known environment, structural elements like corridors, rooms, or halls may differ. Corridors in different places in the same building may have various width, length and illumination sources. The number of rooms and their shapes depend not only on floor but also on the usage of those rooms, etc.

4.1 The interface with the user

Among the ideal features of the flexible interface we should include a) a voice interface, b) a touch pad interface, and c) a shared memory system. This interface should be able to adapt itself to the different user abilities to allow her to control the chair, navigating as smoothly and safely as possible (see §2.3). For example, the agent controller should be able to react to orders like *Stop!*, *Watch out!* or *No* when it is performing a given plan.

The main task of this interface is to interpret users' commands that could be noisy, imprecise and/or incomplete and transform them in *plausible* orders and plans (§4.3). Most of the times the user would be able only to say *what* is she willing to do, *where* is she willing to go (through a voice interpreter or a touchpad), leaving to the agent controller to figure out *how* to achieve it. These orders have to be integrated in the environment and follow the user's preferences. This implies that the agent supporting the interface should have knowledge about the current status of the world. In [15] different approaches to interfaces are presented.

4.2 The multi-level architecture

In order to provide the proper healthcare management we propose a Multi-Agent System that controls the behaviour of the Wheelchair, monitors the patient's health and interacts with him through a flexible interface that gives to the patient, depending on their individual capabilities, more or less assistance in the navigation. Most of the times the navigation will be assumed by the agent controller. The wheelchair will be wirelessly connected to the environment. In order to filter all the information exchanged, each room is monitored and controlled by a multi-agent system. This agent-based controller can proactively take decisions about the room conditioning or process the sensor signals in order to extract meaningful information (i.e. to track a given person in the room).

Figure 2 depicts an example of architecture. It is composed of three levels:

- In the lowest level there are all the devices that are connected to the environment. This level includes the cameras and sensors attached to the walls,

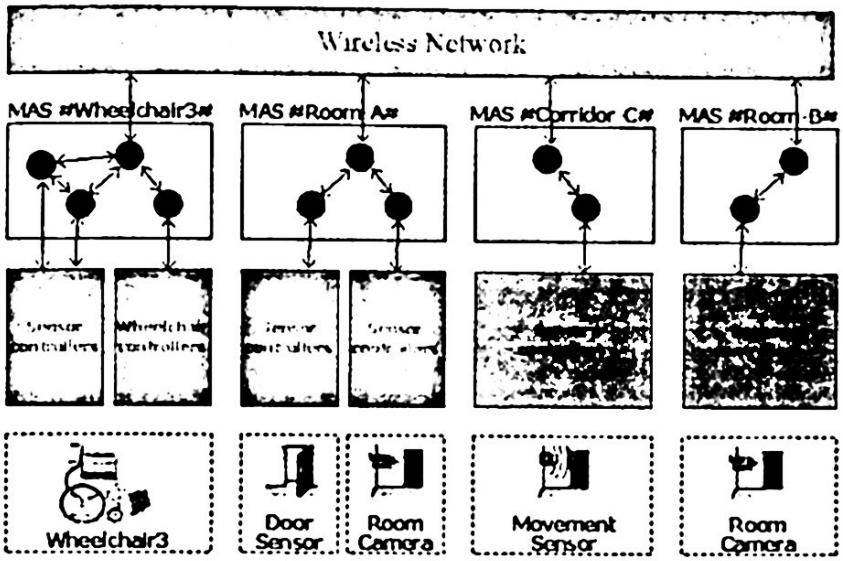

Fig. 2. The proposed multi-level architecture.

patient monitoring systems, PDA's or other portable devices and intelligent wheelchairs.

- The next level is composed by the hardware controllers, that operate the devices and send the information to the next level. In the case of complex devices such as wheelchairs or cameras, this level also should perform tasks that need an immediate actuation of the device (in the case of the camera, a behaviour to follow a person that is being tracked, in the case of the wheelchair, an effective obstacle-detection and avoidance -*reactive navigation*- to ensure a high level of occupant safety).
- The third level is composed by agent-based controllers, which receive the information from the hardware controllers and are then able to reason about the knowledge they have about the state of the system, *what* information they need to improve their knowledge, *where* to get it, and *how* to get it. They can also reason about the *relevance* of the information they receive and distribute it to other agents or controllers that may need it.

This architecture supports the interaction and coordination of all connected entities to solve some of the daily problems patients and care- givers should cope with. For example, the architecture can route alarms when a patient enters (or will enter) a dangerous state as follows:

- Initially, either the caregiver generates a request for information on a given patient or the monitoring system detects a hazardous sensor reading and generates a request for a caregiver. This request is propagated to the third level of the architecture, where it can be handled by the software agents.

- The third level of the architecture interprets the request and asks for information from the lower levels of the architecture to decide a course of action.
- Despite the goal of the process, the location of either a caregiver or a patient is requested. In a small wireless network of active beacons, a given device is captured at most by two beacons so that its position can be inferred by triangulation. If no precise position information is required, this localization can even be performed by covering each room with a single receiver so that it provides information only on the presence of a given patient or caregiver in the room. The third level of the architecture distributes a request for the position of a caregiver or patient to the first level architecture including the positioning devices of all rooms.
- If the caregiver has requested for information on a patient, a low level request for its monitoring sensors is directed to the located patient. These sensors transmit their readings to the closest node of the wireless network and the top level of the architecture redirects the information to the petitioner. If a danger situation has been detected, the third level of the architecture classifies the located caregivers according to their proximity to the patient in danger and a call is transmitted to the closest one.

Patients may also find the system very helpful. One good example is trying to go where another person (a relative or a caregiver) is. In the case where that person has the PDA connected to the wireless network, the environment may first locate in which room the patient and the person are[12]. Then, if both are in different rooms, the wheelchair multi-agent controller, with the help of the environment, builds a plan to go from one room to the other. The wheelchair then executes the plan, carrying the patient to the room where the target person is. If the target person moves from one room to another, the environment forwards this information to the wheelchair, which adapts the plan accordingly. The wheelchair may also report to a human supervisor and ask for help when encountering problems it cannot handle. This problem is analogue to the previously described one.

A more complex scenario happens when the target person has no connected device to the system, either because it is turned off or it runs out of batteries. In this case, as full recognition is classically a very complex problem, it is easier to keep a history of the position of every possible target in the environment when their devices are off. Basically, if a given device is turned off in a room, a video camera in the room starts to track all mobile objects inside. If a mobile leaves the room, the wireless network in the next room can detect whether it is the one with the device off. If such is the case, its position is updated. Thus, the system has the position of all unidentified mobiles available.

[12] Wireless technologies such as Bluetooth support an inquire protocol to determine if a given node, identified by an unique physical address, is in its covered environment

4.3 The navigation problem

The key piece of the system is the patient's wheelchair. Apart of the connection that provides among the patient and the caregiver, the wheelchair enhances the patient's mobility. Naturally, one of the main advantages of working with a robotic wheelchair is that after the goal of a patient's request has been located in the environment, the wheelchair can move towards it in an unsupervised way. In order to increase the safety of the patient and to choose proper paths, the wheelchair also receives more information from the environment (such as trajectory between the goal and the departing point, provided by the agents in the higher level of the system).

The key issue to solve in the case of the wheelchair is Navigation. The navigation problem is briefed in the following questions: i) *where am I* (localization); ii) *where am I going?* (goal definition); and iii) *how do I get there?* (planning). Localization consists of determining the wheelchair position in a global coordinate system and it is typically solved by measurement, correlation and triangulation. Localization is not easy. Most systems rely partially on odometry. However, slippage errors accumulate in an unbounded way. Furthermore, no odometric information might be available (global localization). Localization can be performed either using on-board or external active sensors (i.e. GPS). In our case we will work with active landmarks (the wireless beacons) to calculate the object position by triangulation.

Planning in the real world is usually complex because of unexpected situations or errors. There are two kinds of schemes [1]: reactive and deliberate. *Deliberative planning* typically relies in a classical top-down hierarchical methodology where the world is represented and processed according to actions and events in a *sense – model – plan – act* cycle. The main disadvantage of deliberative planning is its inability to react fast. Also, a reliable model of the environment is required. *Reactive schemes* directly couple sensors and actuators [4]. Global actions are the result of combining one or more reactive behaviours. Reactive schemes deal easily with several sensors and goals. They are also robust against errors and noise. However, they tend to be less efficient than deliberative ones and often fall in local traps. We propose a *hybrid architecture* combining deliberative and reactive schemes in order to achieve a better performance. It follows a global plan provided by the agents in the third level but modulated by the reactive modules in the second level of the architecture (that is, the hardware controllers of the wheelchair). Basically, this approach (which extends the work presented in [23]) consists of two stages:

- Calculation of an efficient trajectory joining the current position of the wheelchair and its goal. The robot manages an easy to update metric map of the environment by combining any available map and its sonar readings. Then, we extract a topological map from such a metric one (see figure 3) to reduce the instance of the path-planning algorithm so that it can operate in a very fast way. We can use an A* algorithm to extract a path from the topological map. Following this approach, we can recalculate a path each

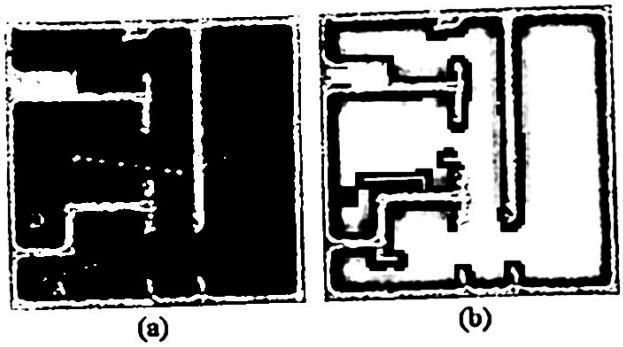

Fig. 3. Deliberative path calculation: a) topological-metrical map, departure and arrival points; b) resulting trajectory and partial goals.

time the goal changes its position or it is impossible to track the previous one further.
- To track the calculated trajectory safely, we have already developed and tested a reactive approach that combines the potential fields approach (goals and obstacles as attractor/repulsor forces) with CBR in order to learn specific solutions to move safely in narrow spaces. [23]

The system described is designed to be placed not only in a hospital (with professional caregivers) but also in the patient's home (where usually relatives play the role of caregivers). The advantages of the system are not limited to the controlled environment where the system runs, though. For instance, when the patient is in a hospital, relatives can be informed of the state of a patient. If the patient is at home, then a doctor may receive periodical reports. To do so, a timer can be set in the higher level to periodically transmit information about the state of the patient. Basically, this service is periodically triggered by an agent in the third level, which can be personalised to set how often the relatives or the doctors want to be updated, but when there's an important change in the state of the patient, the lowest level sends a petition to the third level to send an alert to the relatives. In both cases the agents in the high level filter the sensor information, adapt the information to the accurate level of detail and finally send it to the receiver by means of, i.e., a phone line, an e-mail or even a simple SMS[13] message.

5 CONCLUSION

Assistive Technologies can empower people with disabilities in ways that go far beyond medicine and surgery. The power of AT is still under-recognised by physicians; the potential of AT as an aid to patients is not fully exploited. AT could be seen as a therapy or as a commodity. There are limits on the extent to

[13] Short Message Service, available in mobile phones with GSM technology.

which rehabilitation professionals can help to improve someone's impairments and the broader environments in which he or she lives.

Although existing solutions that increase an independent living for senior citizens are currently available on the market, those are oriented to solve problems in a very poor manner and address a small subset of user's needs. As said in §1, most of them try to solve teleassistance problems, as in [9]. Other just offer specialised information services for the elderly.

We are putting forward this proposal to provide support for disabled and senior citizens. They may be applicable to a wide range of levels and needs, from use by intact healthy people and those with mild cognitive limitation, to providing support for caregivers of elders with moderate impairment and disability. Those systems are devised to provide aid in carrying out activities of daily life, and also performing tasks related to health care maintenance. In addition, they will provide links to the outside world, including entertainment and information, and will facilitate communication with family and the environment.

Among the most important obstacles that new technologies find in real applications in medical informatics we have: user expectations and acceptance, security and trust issues, lack of standards and integration with pre-existing health-care systems. But acceptance of such systems will increase in the future, as senior citizens will be more and more used to interact and rely on advanced technological devices.

We propose here real integration of heterogeneous technologies to serve to disabled and senior citizen with problems as those described in §2 and §3.1 in a non-intrusive way and securing the personal information of the users. It is clear that the use of this new technological devices will help to enhance the quality of life of disabled and senior citizens, their families and reduce institutional and societal costs.

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Agent Based Mobile Collaboration and Information Access in a Healthcare Environment

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Abstract: Hospitals are characterized by a high degree of collaborative work, mobility, and information access from many devices or artifacts. Healthcare environments are becoming ideal test-beds for pervasive and mobile communication technologies. In this paper we present the development of an agent-based mobile collaborative system to support the intensive and distributed nature which characterizes information management and collaboration in a hospital setting. We describe the methodology that was followed to conceive, design, implement and evaluate the prototype. The design is based on a grounded understanding of user needs and the identification of validated scenarios of use, which illustrate that collaboration in the hospital is highly based on a set of contextual elements, such as the location of people and devices and the timing of messages to be delivered. To facilitate the development of the system, we used the SALSA agent middleware which enables to easily integrate autonomous agents to pervasive applications. Finally, we present the results of a preliminary evaluation of the system.

1. Introduction

Information management and communication in a hospital setting is characterized by a high degree of collaborative work, mobility, and the integration of data from many devices or artifacts [11]. Exchanges of information are intense, and demand from participants to promptly extract from the artifact useful pieces of data to perform their job. In contrast with other settings such a traffic control rooms [14], information in hospitals is not generally concentrated in a single place but distributed among a collection of artifacts in different locations. For instance, patients' records are maintained and used in coordination with data on whiteboards, computers, or binders located in rooms, labs, common areas or offices.

Given the high distribution of information together with the intensive nature of the work, it results clear that tremendous coordination efforts are required from all members of the hospital staff to properly manage the information to attend and take care of patients. The right information has to be in the right place, whenever it is needed by whoever needs it, in whatever format (representation) that they need it

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2]. Hence the characteristics of artifacts containing information play a fundamental role to achieve this coordination. For instance, patient's records are easily moved from place to place and filled, checked, read and consulted in many locations like nurses' room, analysis labs, or the actual bed where the patient is being attended; nurses, physicians and other workers interact with those records and use them to support their work or to transmit instructions to be followed by others. To have the patient's records at the right place is what in part makes them successful to support coordination, as well as the fact that the information contained in them is clear, complete, accurate, and updated. Unfortunately those conditions are not always achieved. Documents get lost, instructions are not clear, or the data is not complete to support decisions. We therefore need to understand how each information item gets integrated successfully into artifacts to support the coordination required in hospitals. From that we can derive adequate information technology.

This understanding should be based on a proper assimilation of the context where the hospital's staff performs their job and this demands an active engagement of researchers in daily work through which the routines, procedures, and working practices of individuals can be captured. Therefore our designs aimed to emerge from empirical studies in hospitals and from a comprehensive analysis of the conditions where technology would be implemented.

Figure 1 depicts the process we followed in the design and implementation of a pervasive healthcare application that supports collaborative activities and information access of mobile users. Our workplace study enabled us to understand what and how contextual elements effect the information management and medical collaborative activities: (1) the location of people and devices, (2) the timing of messages to be delivered, (3) the role-oriented nature of the work and (4) the artifact-mediated nature of information gathering.

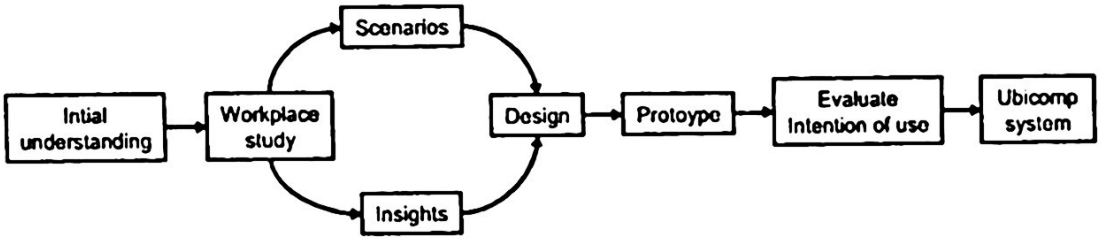


Fig. 1. The user interface of the System's Context-aware Client

We shaped our technological designs to directly address these contextual elements. Thus, our proposed technological solution is a context-aware system based on agents that enables mobile users to collaborate by exchanging messages, and access information and services when and where they need them.

Some of the system's components were identified as agents that respond autonomously in accordance to the context surrounding the activities performed at the hospital. To facilitate the development of the system, we used the SALSA agent middleware which enables to easily integrate autonomous agents to pervasive applications.

The organization of this paper is based in the sequence of steps we follow to conceive, design, implement, and evaluate the system's prototype. In section 2 we briefly review how information management in a hospital setting has been understood

and what has been done to support it. Section 3 describes a workplace study performed to understand the contextual elements supporting the management of information at a hospital. Section 4 presents two scenarios derived from the study that guided the design of the context-aware messaging system. Section 5 presents the findings that resulted from this study. In Section 6 we explain the architecture and design of the agent-based mobile collaborative system, and illustrate its functionality. Section 7 presents the results of a preliminary system's evaluation. Finally, Section 8 presents our conclusions and future work.

2. Initial Understanding of Medical Work Practices

Hospital settings have been a subject of study by many researchers in recent years [3], [11], [12]. Those studies have identified the intensity of the information exchange and its distributed nature. Members of hospital's staff might be distributed in space (i.e. different location within the settings) or time (i.e. working different shifts). Such conditions are clearly not likely to change and are absolutely essential to provide full time coverage for patients.

Consequently given that many people can interact with a patient across the day, all those individuals have to rely on artifacts that serve as containers of relevant patient's data, as well as a channel of communication with other individuals. In her study of a hospital ward, Bossen identified some characteristic artifacts which resulted to be central for the coordination of staff's actions [3]. Elements such as whiteboards hanged on walls, helped to communicate information regarding patients' conditions and locations. Other *mobile* artifacts such as clipboards with individual patient's records provided more details of patients such as the medicine and doses that was administered to each of them. Bossen also emphasizes the importance of having the information in the right place [3].

The effectiveness of information artifacts is highly dependent on their location but also on being able to provide adequate information to the reader. It has been pointed out that due to their different professional background, hospital's personal is likely to experience communication problems or to define and agree on what is the most useful way to represent information contained in artifacts [12]. For instance, physicians and nurses can pull different bits of data from a patient's record in order to do their work (e.g. a diagnostic vs. the administration of medications). Therefore in order to be effective an information artifact has to be *elastic* enough to provide with different levels of representations for each possible reader in such a way that it results meaningful for all of them.

Limited work has been done to directly address the information management needs of hospitals with context-aware technologies that support contextual variables such as where the artifact is located, who reads it, when it is read and for what purposes it is read. Previous efforts have focused on supporting communication among individuals working in hospitals by using video conference [9] or 2-way pagers [7]. Unfortunately those designs do not contemplate that tasks in hospitals are usually handed among people working different shifts [3] and the fact that even when people are collocated

they often rely on information artifacts to transmit data to other members instead of contacting them directly minimizing with this articulation efforts.

Other design efforts have intended to support the mobility inherent in many of the information artifacts used in a hospital. For example the Ward-in-Hand system is a handheld system that provides access to patient's records, hospital information and communication with other patients through a wireless infrastructure [1]. In spite that this solution seems to be pointing to the right direction we believe that it is limited because it conceives information artifacts as being personal devices, which is clearly not the case. Information artifacts in hospitals are in essence shared by many people and consequently we must focus or design on supporting the roles that individuals play and not the individuals themselves.

With the aim of acquiring a robust understanding of what are the essential contextual elements that support the management of information and collaboration in a hospital setting and how they interact with each other, we conducted a workplace study which is described in the next section.

3. Workplace Study

In order to design the agent-based mobile collaborative system we conducted a field study at the IMSS General Hospital (H.G.Z. IV. No.8) in the city of Ensenada, Mexico. This is a public health institution providing medical services for a potential population of 175,000 inhabitants. Our approach was to use qualitative methodologies to gain understandings beyond requirements gathering and understand how routine and non-routine work is performed in a daily basis.

To understand IMSS General Hospital's people, setting, and practices, we studied three of its high-traffic departments: Urgencies, where more than 70 percent of the patients enter the hospital; Internal Medicine; and Laboratory Analysis. Most patients enter through Urgencies and go to Internal Medicine, and they typically require laboratory services. For three months, we observed work practices and conducted interviews with 20 staff, including physicians, nurses, social workers, assistants, a chemist, and lab workers. We took care to select people with different roles, experience, and expertise. We then assimilated our results to gain a deeper understanding of how contextual elements affect information management. From interview transcripts and our written observations, we identified characteristics that context-aware technologies should support. We also identified the processes in which the hospital workers were most likely to interact frequently, change location constantly, and access patient information. We then sorted out activities that depend on contextual variables such as location, identity, role, or time. We modeled these processes and validated them in another set of interviews with workers.

Once we clearly understood the processes, we identified use scenarios —situations that exemplify a distinct and typical use for a context-aware support system. The scenarios below show the kind of contextual support hospital work requires and give a flavor of how technology can enhance hospital practices.

4. Scenarios of Use

The scenarios let us translate our findings into specific vignettes that captured facets of how context-aware and mobile computing technology might fit into current work practices. The scenarios were sketches of user activities. They did not contain details about how the tasks would execute or how the system would enable the required functionality [4]. Rather, the scenarios helped us frame our understanding of hospital work practices and gave us insight into how mobile and context-aware computing could augment the work. This section presents two of the seven scenarios we used to design the system, which are the most representative examples of daily medical work.

Scenario 1:
Rita is a doctor in a local hospital. As she makes her final round, she notices that a patient, Theresa, is not responding well to her medication. Rita wishes to leave a note to the doctor who will be reviewing Theresa in the afternoon shift. She doesn't know who that will be, so she writes a message to the first doctor to check the patient after her.

Scenario 2:
While Dr. Diaz is checking the status of a patient (on bed number 1 of room 222), he realizes the needs to request an ordinary laboratory study for her. Through his PDA, he adds this request to the patient's clinical record of the Hospital's Information System. The chemist (responsible for taking the samples for the analysis) visits the internal medicine area every morning. His PDA informs him that inside room 222 there are three patients that require a medical analysis. When the chemist stands in front of the patient, his PDA shows him the samples that have to be taken and the type of analysis to be performed. He labels the samples and at the end of his round he takes them to the lab to perform the analyses. The results are added to the patient's clinical record. When the doctor is about to finish his shift and while walking through the corridor, his PDA alerts him that the test results of the patient on bed number 1 in room 222 are available. Dr. Diaz goes back to the patient's room and when he stands near the patient's bed the results of the analysis are displayed on his PDA. At that point, the doctor revaluates the patient and based upon the results just received, decides to prepare him to be surgically intervened.

5. Insights from the Study

We group the findings from our study into four different aspects that let us to understand the fundamental contextual elements that have to be considered to support the management of information and coordination of activities

5.1 Location of people and devices

We noticed that the location of hospital's staff is useful to determine the type of information that they might require. Access to patient's medical records is most relevant when the doctor or nurse is with that particular patient. It is in the context of the patient's bed when detailed information should be revealed to the adequate person. For instance a nurse might notice that a particular medicine has to be administered to a patient and she must know the appropriate doses to apply to the patient. Location then becomes relevant when considering what information to deliver. This information should be sent to the place where it will be useful rather than to a particular person. We conclude that an approach that emphasizes the role of location and integrates it into its design will protect against overloading the hospital's staff with information which is neither useful nor relevant at that particular location.

5.2. Timing for the delivery of information

Communication exchanges in an intensive working environment such as a hospital tend to be time-sensitive. There is a period of time during which a message is relevant to be delivered. For instance, a doctor might wish to leave a message providing recommendations for the treatment of a patient, to any nurse of the next shift. The message might not be relevant if delivered before the next shift since not enough time has passed to evaluate the evolution of the patient's symptoms, nor will it be relevant the following morning. We conclude that an approach that lets users specify the time where messages are delivered will facilitate the coordination of activities in a hospital where services are provided 24 hours a day, 7 days a week.

5.3. Role-oriented nature of work

Communication needs to be established between parties that might not know each other a-priori or which rarely meet. For instance, we noticed that due to the work-shifts and the constant turnover of personal, a single patient might be attended by two different physicians and three different nurses in the same day. In such conditions communication of messages is not addressed to particular individuals but to the nurse in the afternoon shift, the next doctor to visit the patient, etc. There is not certainty about who will be that person, only about the role that he/she will play in the attention of the patient. Therefore information is often sent to roles and not particular individuals. We conclude that an approach that complements communication with specific role-based support will be more appropriate for hospital work.

5.4. Artifact oriented nature of information gathering

Awareness of the state of an artifact (e.g. patients' records) facilitates the communication among coworkers and reduces the chances of misunderstandings. For instance, the state of devices (temperature reading) and documents (availability of lab results) can be important triggers for information exchanges. The sudden availability

of a bed could trigger the transfer of a patient waiting in the corridor of the emergency room to the next bed to be freed. Medical staff might need to communicate directly with documents and/or devices. For instance, a doctor might wish for the patient's lab analysis to be shown on the large display of his office as soon as they become available. We conclude that through the monitoring of relevant artifacts we can support the timely delivery of pertinent information to hospital workers.

6. Supporting Mobile Collaboration and Information Access in Hospitals

In this section we present the design of an agent-based system to support context-aware collaboration and information access of mobile users. Thus, we first introduce the concept of context-aware computing, and present the system designed to support the scenarios described on the previous section.

Context-aware computing has been closely associated to pervasive computing [6] Context-aware computing refers to an application's ability to adapt to changing circumstances and respond based on the context of use. Mobile users are constantly changing their context, most notably their location. Additionally, context-awareness often requires the use of sensors and computing devices set in the environment in order to establish the context of use.

As noted in the scenarios presented in Section 4 there are circumstances, in a hospital setting, that require the sending of messages to a person or device that might depend on contextual information (location, time, availability, etc.). For instance, the doctor in the first scenario described might wish to send the message to the first doctor to be at a particular location (around a patient's bed) during the afternoon shift and once the results of his medical analyses have been reported. Another scenario might involve a doctor wishing to send the lab results to the first printer to become available or to be visualized in a public display for consultation with another doctor.

Based on these scenarios we decided to use the Instant Messaging (IM) paradigm to support what we refer to as context-aware communication. In particular we look to support context-aware messaging. This concept extends the traditional instant messaging paradigm by allowing users to specify a set of circumstances that need to apply for a message to be delivered; we refer to this as context. For example, the sender can indicate that the message will be delivered to the specified recipient when she enters the emergency room; or for the message to be sent to the last person to leave the laboratory when the air conditioning is on.

Some of the key computer-based components of the proposed scenarios can be envisioned as agents that have capabilities to make their own decisions about what activities to do, when to do them, what type of information should be communicated and to whom taking into account the situation's context. Such capabilities have been identified as features highly related with autonomy [8]. We also observe in these scenarios, that a user could interact seamlessly with a range of different agents that can assist the user in his activities. These autonomous agents enrich context aware computing environments by introducing capabilities for negotiating services with other agents and wrapping complex system functionality. For instance, autonomous

agents can monitor the medical information system in order to notify to a doctor when the results of a medical analyses are available; find out what is the nearest public display where a doctor may discuss the analyses results with a medical specialist; control and allow access to the hospital's devices/services taking into account priorities or security restrictions; estimating users' localization; and monitoring the environment to control the sending of contextual messages.

6.1 System's Architecture

The functionality of the agent-based system is illustrated in Figure 2. It uses a client-server architecture as a basis for its implementation. Wireless connectivity between servers and mobile clients is achieved through 802.11b access points. We incorporated autonomous agents into our system architecture, along with a context-aware client and an IM server, which are explained next.

Instant Messaging Server
We used and extended the Jabber open-source IM server (www.jabber.org) and its Extensible Messaging and Presence Protocol XMPP (currently an Internet Engineering Task Force draft). This server is used to notify the state of people and agents, and to handle the interaction between people, agents, and devices through XML messages. All communication between the Context-aware Client and the Context-aware Agent will go through this server. The information in the user's handheld is synchronized with the server every time the device is connected to a point of access.

Context-aware Client
In traditional IM systems messages are sent as quickly as possible. In these cases, of course, the identity of the recipient is known a-priori. This won't work for context-aware messaging where the recipient's identity won't be known until a specific state is achieved. One of the components of the Context-aware Client is a lightweight interface for users to compose the message and to easily specify the context of delivery, which is record by the Context component, also responsible for requesting the user's location to the Location-estimation Agent. Given that the messages are not necessarily sent immediately after they are composed, the system should allow users to go back, consult the messages they have sent, and modify or delete them. From the perspective of the user that receives a context-aware message, it might be important to be aware of the context specified for message delivery, since this information could be useful for him to make sense of the message. For instance a message that states "medicate this patient when his analyses are completed" might not be fully understood if the user is not aware that the message was meant for delivery at a specific location, the patient in certain room in this case.

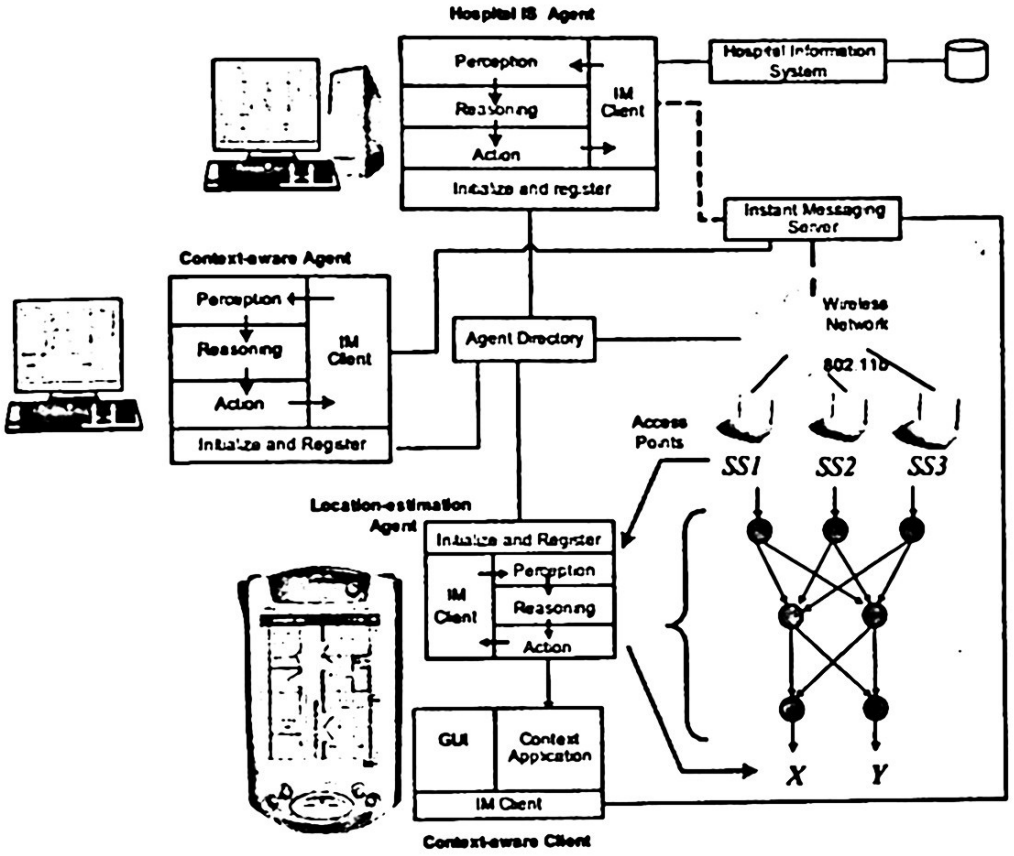


Fig. 2. Architecture of the agent-based system to support context-aware medical work

Agents

Several software components of the system are agents that autonomously act according to the perceived context information. In order to facilitate the implementation of autonomous agents for this pervasive system, we used a development framework called SALSA (Simple Agent Library for Seamless Applications). This framework provides a set of abstract classes and mechanisms to develop autonomous agents that act on behalf of users, represent services or wrap a system's functionality [13].

A SALSA agent can be launched explicitly by the user or automatically when certain conditions are met. Agents might run in a user's PDA, a trusted server, or any other computer with connectivity to the access point. A SALSA agent contains several components: a protocol to register it with an Agent Directory; a Jabber client through which users, user's agents, and services' agents interact by sending XML messages; and finally, the subsystem that implements the agent's autonomy that includes components for perception, reasoning, and action. The perception module gathers context information from the environment's sensors or directly from the users, other agents, or services through an IM client. The reasoning subsystem governs the agent's actions, including deciding what to perceive next.

Figure 3 shows the main classes provided by SALSA which enables to implement the internal architecture of an agent. The Agent class provides the methods to create

and control the agent's life cycle. The agent's perception module consists of several Perception objects which sense the environment to gather context information. The framework provides the EntityToPerceive class that allows getting information directly from a sensor or the memory of a computer system. When an entity has new data, then it notifies to all Perception objects attached to it. The implementation of this perception module is similar to the Observer software pattern, which can be used when an object needs to notify other objects without making assumptions about who these objects are [15]. The Reasoning class contains abstract methods that will be implemented by the developer. Its implementation depends on the complexity of the agent's behavior. Finally, the Acting class provides an abstract method that a developer will implement to specify how the agent should react.

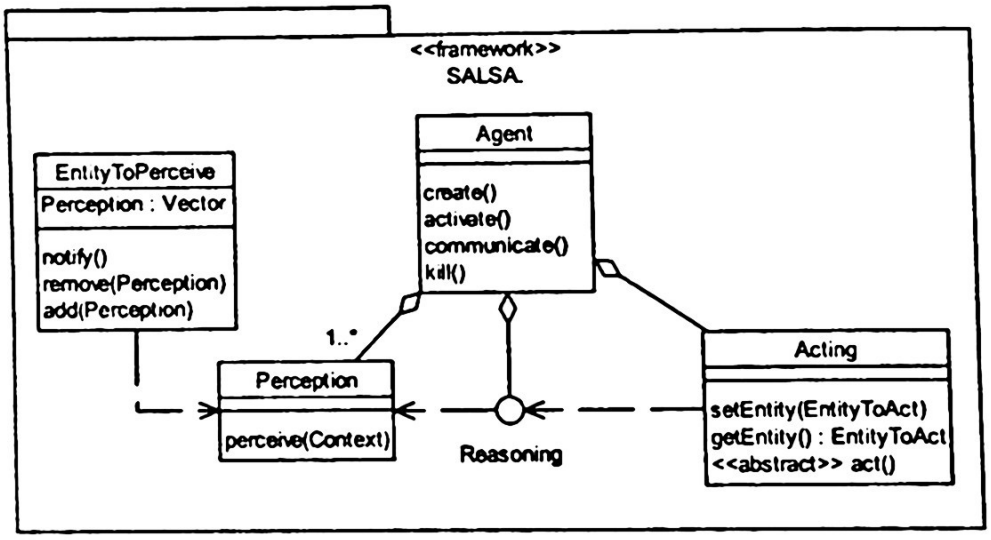


Fig. 3. Architecture of SALSA development framework

The system includes the following Agents:

- *Context-aware Agent* that supports the delivery of messages that are dependent on context. This is an entity to which all context-aware messages will be sent. The Context-aware Agent will monitor the environment to determine whether conditions are met for the delivery of the messages it retains. Its perception module registers the contextual information by monitoring the environment through the context interface. The context interface consists of a component to configure the environment (devices available, groups of users, map of the site, etc.) and mechanisms to detect changes in contextual information, such as, devices' state, users' position, etc. The reasoning component analyses the contextual information to determine if the conditions specified by messages it stores are met. If this is the case, the action module triggers the event specified by the user, which can consist of sending a message to any user with a specific role, or sending a message to a device in order to use its service or change its state. Thus, the Context aware Agent is a first class entity registered in the instant messaging server and with an IM roster that includes all people and devices of whose state it needs to be aware in order to deliver the messages it receives.

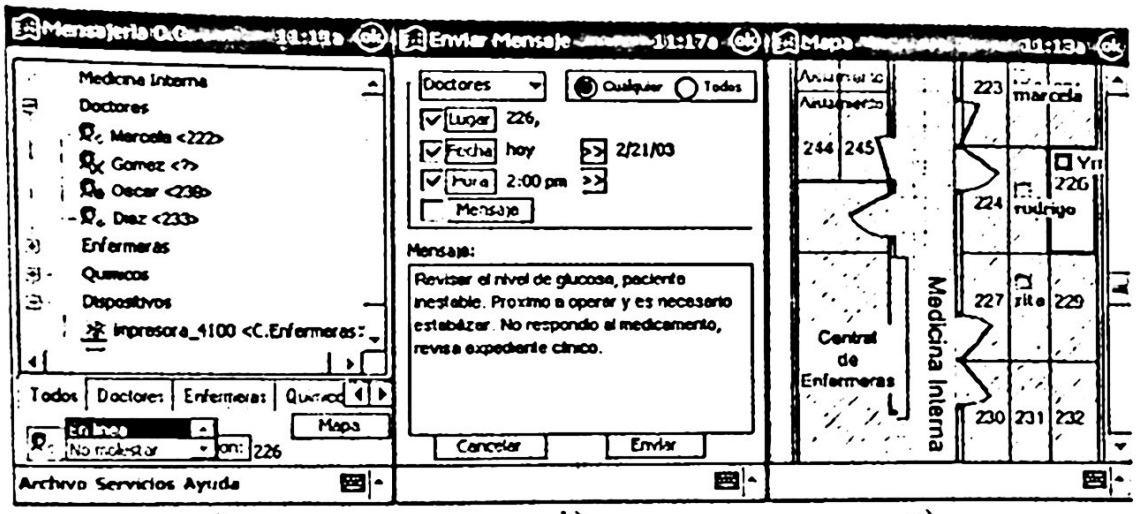
- In the user's PDA resides a *Location-estimation Agent*, which obtains the user's position by triangulation of at least three 802.11b access points [2]. Its reasoning component wraps a back propagation neural network, previously trained to map the signal strength obtained through the agent perception module from each access point to the user's location. Thus, the Context-aware Client updates its user's position information by communicating with the Localization-estimation Agent.
- The *Hospital IS Agent* provides access to, and monitors the state of, the Hospital's Information System which stores the patient's clinical records and other data relevant to the hospital, such as what patients are in what beds. For instance, considering the second scenario of Section 4, when the agent detects that the IS has been updated with the results of the user's laboratory analysis, the Hospital IS Agent notifies the doctor. It is also used to provide patient's information to the medical staff, based on their role and location.
- *Agents as proxies of devices.* Devices are appliances that offer services and are connected to the local network. Devices define possible states, the services they offer, and the protocol used to interact with them. Communication with a device is made through its agent, which runs as a daemon on a computing device with connectivity to an agent directory and a Jabber server. Agents provide a standard mechanism to initialize and register the agent with one or more agent directories, which contain information of all services offered in the environment.

6.2 A Sample Application Scenario

We illustrate the use of the context-aware messaging system revisiting the first scenario presented in Section 5. As Rita, the physician in turn checks her last patient, she decides to send a message to the doctor who will be reviewing the patient in the afternoon shift. She turns to her PDA showing the Context-aware client, which lists the staff and devices available in the hospital, to send a message to the first doctor to check the patient during the next shift. As illustrated in Figure 4a, this client is able not only to notify the status of other users (e.g. Online, Busy, Disconnected, Away, etc.), but also to show resources available in the vicinity (such as printers, air conditioning systems, etc.) and their status as well as the services they can provide to the user. In addition to the information provided by an instant messaging system, the Context-aware Client also shows the location of users and devices if known. This information is shown parenthesis after the user's name as shown in Figure 4a.

In contrast with traditional instant messages, when a context-aware message is created the sender needs to specify the circumstances that need to be met for the message to be delivered. Figure 4b shows the interface used by Rita to write the message and specify the context for its delivery. Rita writes the message and specifies that it should be sent to *any doctor* to be in *Room 226*, *after 2pm*, *today*. Through the interface shown in Figure 4b users can specify the following information to provide adequate context for the delivery of the message:

Recipient. The user can send a message to a specific user; to all users that meet the additional criteria; or only to the first user that satisfies the criteria. In our current prototype the sender specifies the recipient's identity by role (such as, a doctor, nurse, etc.) in the case of the scenario; Rita sends a message to any doctor in the next shift.



a) b) c)

Fig. 4. The user interface of the System's Context-aware Client

Location. The sender specifies an area where the user needs to be located for the message to be delivered. For this purpose a sensitive hospital map is displayed for the user (Figure 4.c), where she selects the designated area, for instance, Rita selects the room where she is currently located, patient's room 226.

Time and date. The sender can specify a lower and upper bound of time and date for message delivery. He could specify either one or both. The message won't be sent before the minimum date indicated and will expire without delivery after the maximum time. As Doctor Rita wishes to send the message to the doctor in the next shift, she specifies the period of time of delivery to be after 2pm.

State of a device. This is another context variable that a user can specify. Devices define the set of all possible states in which they can be at a given time. This list of states for all registered devices is presented to the user if he wants to specify that the device needs to be at a given state as a constraint for message delivery. For instance, send the message if the lights are on; the printer is jammed; the camera has detected movement; etc. We have already integrated only two devices in the system, a laser printer, and remote-controlled video camera.

Now that Rita has sent the message we describe how the components of the system's architecture interact for its delivery. Figure 5 presents a sequence diagram illustrating this process.

Doctor Gomez, the physician in that afternoon's shift, begins his daily routine by visiting each one of his patients. While he moves around the patient's rooms, the Context-aware Client in his PDA communicates with the Location-estimation Agent, to constantly update his position. When his location changes the Context-aware Client sends, trough the IM server, the doctor's presence to all users and agents who have him registered in their rosters. When doctor Gomez enters Theresa's room, the Context-aware Client updates his presence and notifies this to the Context-aware Agent. As the message's delivery conditions match the new context, the Context-aware Agent sends doctor Gomez the message written by Rita.

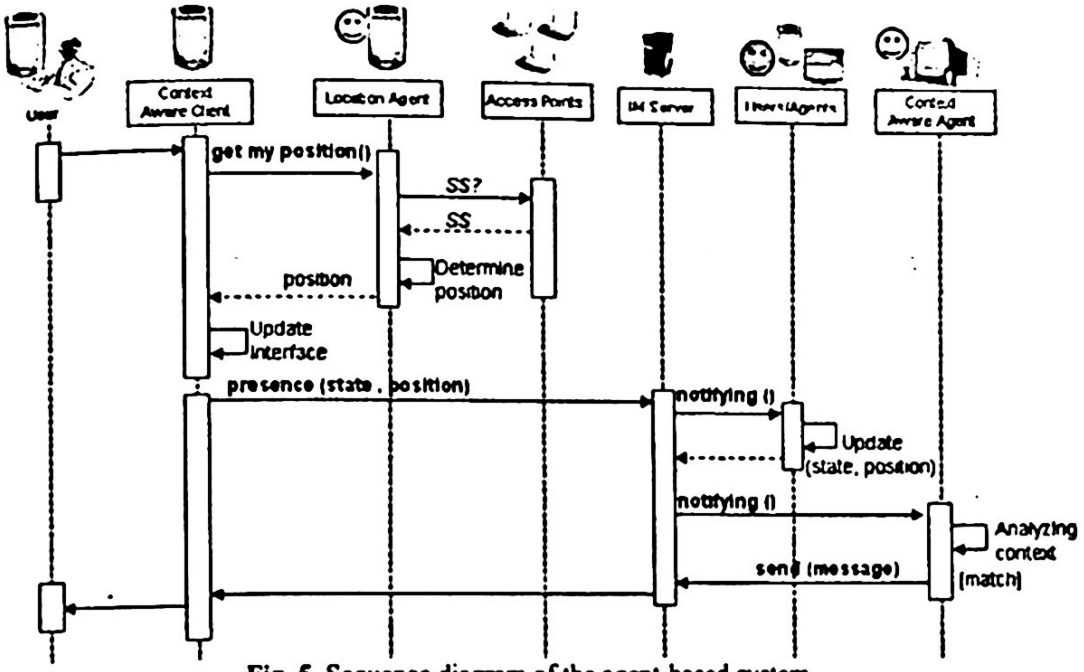


Fig. 5. Sequence diagram of the agent-based system

Figure 6 illustrates how the contextual message is displayed in the doctor's PDA. The recipient of the message can also request the conditions that were defined for the message to be delivered which should provide him with additional context to understand the message received.

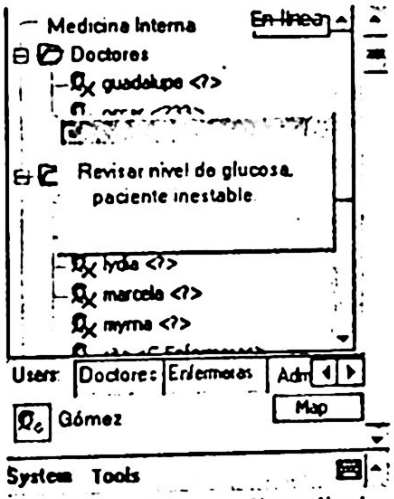


Fig. 6 Doctor's Context-aware client displaying a message

7. Preliminary Evaluation

A preliminary evaluation of mobile and pervasive technology is important before actual deployment and investing on the required infrastructure. Our approach was to conduct a session (Fig. 7) with personal from the General Hospital of Ensenada where

we could evaluate the system's core characteristics, the staff's intention to use the system, and the staff's perception of system utility and ease of use. According to the Technology Acceptance Model [5], these aspects are fundamental determinants of system use.

The session's participants (28 medical staff) validated both scenarios and provided us with additional insights and opportunities for applying our technology. The results of the TAM questionnaire show that 91 percent of the participants would use the system. Additionally, 84 percent believe that using the system would enhance their job performance -a high degree of perceived usefulness- and 78 percent perceived the system would be easy to use.

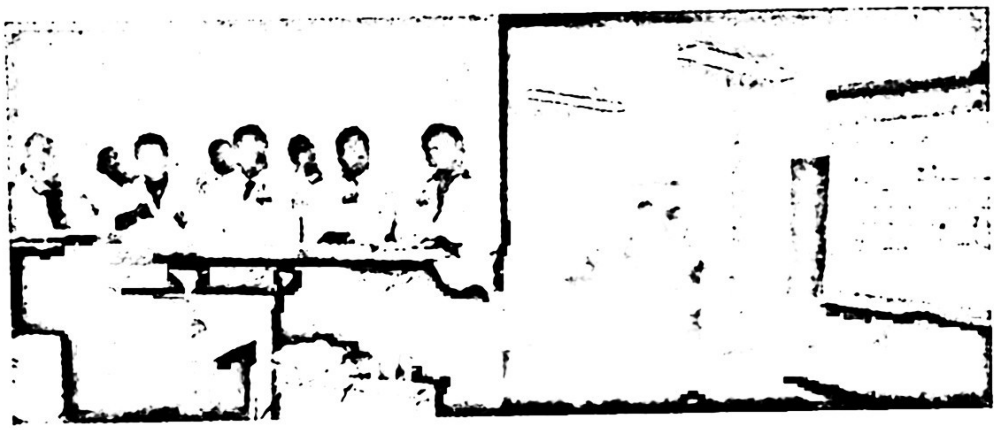


Fig. 7. Evaluation session of the system.

8. Conclusions

This paper presents and describes a context-aware messaging system which was specifically designed to support the contextual elements defining information management and collaboration at hospital settings. Ethnographic methods (namely participant observation and interviews) and scenario evaluations were used to define and clarify how contextual elements shape artifacts and influence work practices at hospitals. We found that hospital workers are highly mobile, working at different locations and shifts. The intensive information exchange between hospital's workers and their interaction with artifacts is highly dependent on situational information, or context [6], which can change unexpectedly. The above issues were addressed with the design of a context-aware collaborative system based on the instant messaging paradigm, which has proven to be an efficient interface to support collaboration and opportunistic interaction. It provides an adequate balance between awareness, privacy and disturbance.

The system we have presented allows mobile users to send contextual messages and access services by taking context into account. We used an agent-based architecture to facilitate the system's implementation. These components are autonomous agents that wrap complex system functionality, such as calculating the user's location, or deciding when to deliver a message; and introduce capabilities for

negotiating services with other agents. Developers that wish to add a new device to the context-aware messaging system need only to program an interface to the device and define an XML document to specify the interaction with the services it provides. No changes are required to the Context-aware Client application used to interact with the environment. Furthermore, the states defined by these devices can also be used to specify the context required for message delivery.

The context-aware messaging system could be easily adapted to support scenarios in other areas, such as, in an educational environment. The system provides configuration options that allow users to initialize and modify the contextual space in order to specify the roles defined for its users (teachers, students, etc), a map of the location (a library, a school department, etc), and the services relevant to the application domain.

We believe that further research has to be conducted to understand how contextual elements could be supported in other settings and also to understand the evolving processes defining the relationships between those elements. Our future work will explore those issues. The work presented here is a first effort to understand those aspects within a hospital setting. However this initial work paves the way to define a robust technological architecture to support the contextual characteristics of work practice whenever it is conducted.

Acknowledgments

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Knowledge Discovery Applied to Medical Domains

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Abstract. The high production rate and the variety of medical data makes necessary the use of new tools to analyze it and get the best from it. Knowledge discovery in databases (also known as data mining) is a research area that comes from the combination of the machine learning, statistics, and pattern recognition areas. In this paper, we apply data mining techniques to two medical domains. In the first domain, we use decision trees and neural networks to detect calcifications in mammograms and in the second domain we use decision trees to analyze a tuberculosis database. Our results show that data mining techniques can be efficiently used to detect calcifications in mammograms with a predictive accuracy of up to 94 % in the ISSSTEP mammograms database and can also be used to find descriptive patterns that help us to understand the increase in cases of people with tuberculosis in Tlaxcala, Mexico.

1 Introduction

The technological advance in the medical area has contributed not only to the automation of complex processes but also to the production of large amounts of data in hospitals. There are a rich variety of medical databases that go from diagnosis data to radiological images. The large amount of stored data needs to be analyzed to find patterns that cannot be found with standard tools (like statistics or spreadsheets). Here is where knowledge discovery techniques can be applied to medical datasets to find hidden patterns from them. In the rest of this section we describe the knowledge discovery in databases process. In section 2 we present our research in the calcifications detection in mammograms domain and in section 3 we show our work in the tuberculosis domain. Finally, in section 4 we present our conclusions and future work.

1.1 Knowledge Discovery in Databases

Knowledge Discovery in Databases (KDD) is a field of computer science concerned with finding patterns or interesting knowledge in large databases where it is not possible to manually identify these patterns due to the large amount of data. KDD has been technically defined as "the non-trivial process of identifying valid, novel, poten-

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tially useful, and ultimately understandable patterns in data" [1]. From this definition, we see that KDD is a process that involves several activities: data preparation, search for patterns over the prepared data, evaluation of those patterns, and refinement of the whole process (see figure 1). The definition also states that patterns should be valid, novel, potentially useful and ultimately understandable. A pattern is valid if it applies when new data is added to the database. Novel patterns are those that show facts that we did not know were in the database. The patterns are useful when the corresponding knowledge can be used to improve something in the field that the data was taken from. The patterns must also be understandable so that the user is able to identify and use the new knowledge.

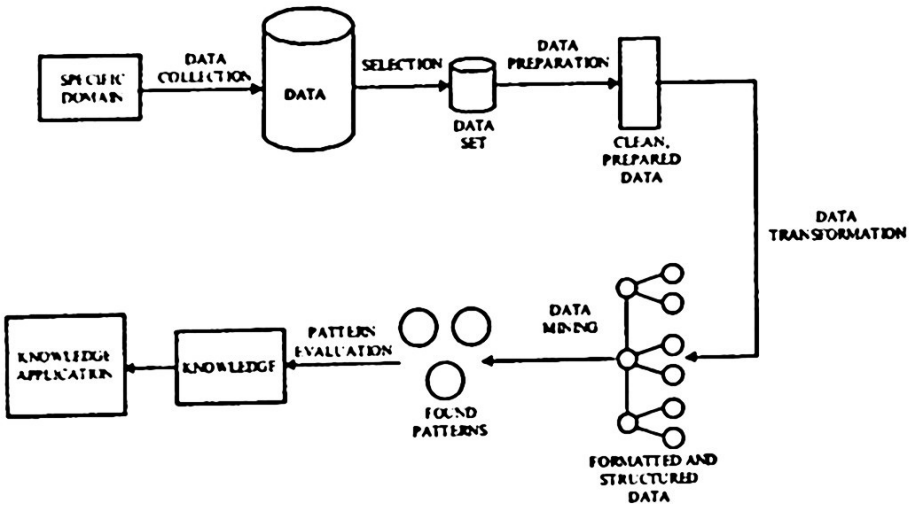

Figure 1. The KDD Process.

The KDD process also includes a pattern evaluation phase so that we can identify when the pattern is considered new knowledge or if it is just irrelevant information. We can do that by grading the patterns according to their characteristics like how useful and novel is the pattern and assigning a threshold over that grade. Only if the pattern grade is higher than the threshold is it considered new knowledge. The KDD process steps can be enumerated as:

- Identify and understand the application domain.
- Choose and create the set of information to be used in the process.
- Prepare the data for the process.
- Choose the data mining task.
- Choose the data mining algorithm.
- Execute the data mining algorithm.
- Evaluate the found patterns.
- Apply the discovered knowledge.

Figure 1 shows how the KDD process is related to the information, concepts and tools we just mentioned. In the following sections we will see how we applied the

KDD process to the calcifications detection in mammograms and the tuberculosis domains.
In the following sections we briefly describe the data mining algorithms used for this research. We start with Neural Networks in section 1.2, then we describe decision trees in section 1.3 and finally, we introduce Subdue in section 1.4.

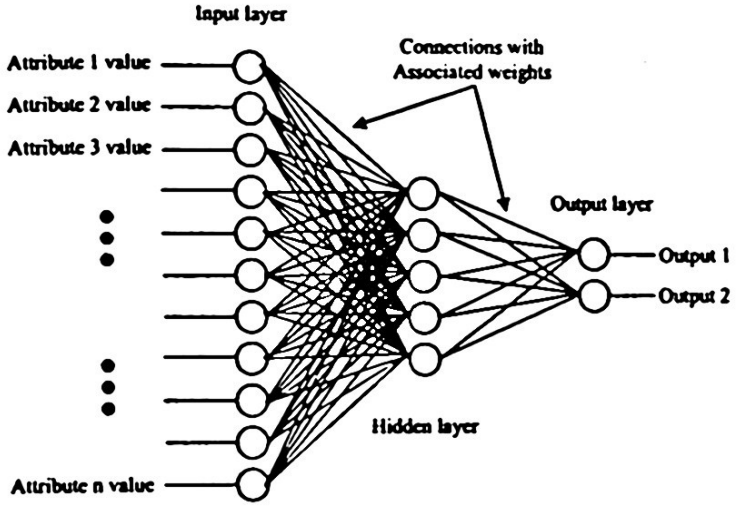

Figure 2. Neural Network Architecture.

1.2 Neural Networks

For a long time researchers have tried to simulate how the human brain works with mathematical models called neural networks [7]. A neural network is composed of a set of cells that are interconnected in a layer fashion. The first layer is called the input layer and its function is to pass the input signals to the next layer. Each cell in the next layer (intermediate cells) receives a signal from each cell in the previous layer modified by a weight factor. The intermediate cells calculate their signal according to a function over its input signals, in the case of the backpropagation algorithm that we use [7], the new signal is calculated with the sigmoid function and then passed to the next layer cells. Once the signals reach the output cells, the result is compared with the real classification of the input feature vector and the error is propagated to the previous layers by adjusting the weights of each connection between cells. In our work with the calcifications detection in mammograms domain, we use a Neural Network (NN) with 11 input nodes, 1 hidden layer with 5 nodes and two output nodes. As we can see in figure 2, the input nodes receive signals from the feature vector and the output nodes show the classification of the NN for the given input vector. In the case of the calcifications detection domain, the possible classifications are positive (the feature vector corresponds to a calcification) or negative (the feature vector does not correspond to a calcification). The NN is trained with the back propagation algorithm comparing the actual output of the network with the real output for each input vector and changing the weights of the network to reduce the output error.

1.3 Decision Trees

Decision trees [8] are a classification method that generates a tree to classify a set of input examples according to their class. Each branch in the tree represents a decision. Each node in the tree refers to a particular attribute. Edges connecting nodes are labeled with attribute values and leave nodes give a classification that applies to the examples that were reached through that branch. At each step of the tree construction, a node is selected according to a statistical measure called information gain that measures how well a node (attribute) distributes the input examples with respect to their class. Figure 3 shows part of an example of a decision tree for the calcifications detection domain. As we can see, the root node for the tree is the area node. If area has a value of less or equal to 13, we verify the value of the diameter attribute. If diameter has a value of less or equal to 2 then the class of the example is positive. If the value for diameter is greater than 2, we verify again the value of the diameter attribute and if it is less or equal to 2.83, we verify the convexity attribute. If the convexity attribute has a value of less or equal to 0.93, the class is positive, otherwise the class is negative.

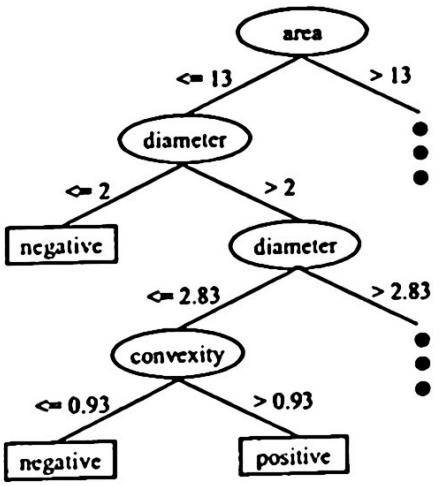

Figure 3. Partial Decision Tree.

1.4 Subdue

Subdue ([4], [5]) is a relational learning system used to find substructures (subgraphs) that appear repetitively in the graph representation of databases. Subdue starts by looking for the substructure that best compresses the graph using the Minimum Description Length (MDL) principle [6], which states that the best description of a data set is the one that minimizes the description length of the entire data set. In relation to Subdue, the best description of the data set is the one that minimizes:

$$I(S) + I(G|S)$$

where S is a substructure found in the input graph G, $I(S)$ is the length (number of bits) required to encode S, and $I(G|S)$ is the length of the encoding of graph G after being compressed using substructure S.

After finding the first substructure, Subdue compresses the graph and can iterate to repeat the same process. Subdue is able to perform an inexact match that allows the discovery of substructures whose instances have slight variations. Another important characteristic of Subdue is that it allows the use of background knowledge in the form of predefined substructures.

The model representation used by Subdue is a labeled graph. Objects are represented by vertices, while relations are represented by edges. Labels are used to describe the meaning of edges and vertices. When we work with relational databases, each row can be considered as an event. Events may also be linked to other events through edges. The event attributes are described by a set of vertices and edges, where the edges identify the specific attributes and the vertices specify the values of those attributes for the event. Figure 4 shows the star graph based representation that we used with Subdue for the tuberculosis domain. As we can see in figure 4, vertices represent either objects as in the case of the "EVENT" node (there is an event vertex for each case in the database) or attribute values as in the case of vertex labeled "2002" that corresponds to the value of attribute "Year" that appears in the label of an edge. This graph-based representation applies for a flat domain but graphs can be used to represent complex structured domains such as chemical compounds.

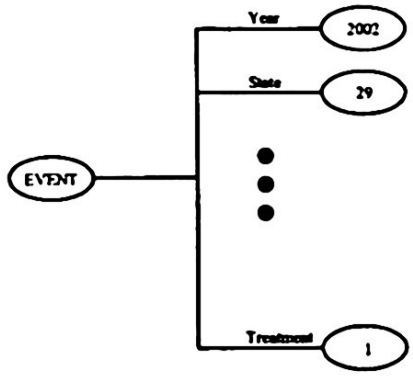

Figure 4. Graph-Based Representation for Subdue

After describing the KDD process and the data mining algorithms used in this research, the following sections show our work in the calcifications detection in mammograms and the tuberculosis domains.

2 Calcifications Detection in the Mammograms Domain

Breast cancer is the second cause of death for women with cancer after cervical uterine cancer and is considered a public health problem. According to statistical data from INEGI, breast cancer was the 12th cause of death for Mexican women with 3,574 deaths in 2001.This is the reason why we decided to attack this problem and found that early detection is one of the best measures to do this. We are working with Dr. Nidia Higuero from the ISSSTEP hospital and created a database of mammograms, which is described in section 2.1. Our domain expert selected the set of cases and gave them to us for scanning. After the images were digitized, Dr. Higuero put marks to those images with calcifications in the places where those calcifications were found; we will refer to these marked images as positive mammograms. We needed these marked images for training purposes, as we will mention in the methodology section. The goal is to find patterns describing calcifications so that we can use them to predict the existence of calcifications in new images and provide the radiologist with a second opinion of his diagnosis. Since our dataset consists of images of mammograms, we need to preprocess the images and create a dataset with the desired characteristics corresponding to those Regions Of Interest (ROI's) known as calcifications. For the preprocessing step of the mammograms we used the machine vision techniques described in the methodology section.

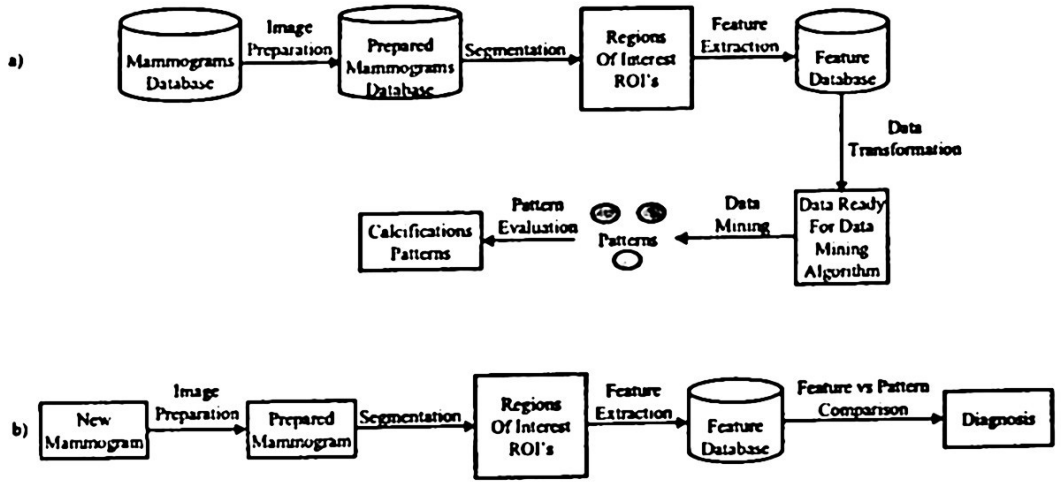

Figure 5. KDD Process Applied to Find Calcifications in Mammograms. a) Training Phase, b) Diagnosis Phase.

2.1 Database

For our experiments we are creating a mammograms database in coordination with our domain expert, Dr. Nidia Higuero from the ISSSTEP hospital. Until now, we have a set of 84 cases of mammograms (one case per patient), each case contains four images, one craniocaudal and one oblique view of each breast. The images were digi-

tized with an Epson Expression 1680 fire-wire scanner at 400 dpi's, with a size of 2,500 x 2,500 pixels in bmp format. From the 84 cases, 54 have calcifications and 30 are normal (with no calcifications). Our domain expert selected the set of cases and gave them to us for scanning.

2.2 Methodology

The combination of machine vision and data mining techniques to find calcifications in mammograms is shown in figure 5. Figure 5a shows the knowledge discovery in databases (KDD) process that we use to find patterns that describe calcifications from known images (those images for which we know if they contain calcifications or not). The process starts with the image database that consists of the original and marked mammograms. As we mentioned before, marked mammograms identify where calcifications are located in a positive mammogram. An image preparation process with a wavelet filter is applied to these images to make calcifications easier to detect. After this, a segmentation algorithm is applied to each positive image in order to get our positive ROI's corresponding to calcifications. A different segmentation algorithm is used to get our negative ROI's, that is; regions of interest of areas that are very similar to calcifications but that are not. After this step we have a ROI's database where each ROI is classified as positive or negative. Next we apply a feature extraction process to each region of interest to create a feature database that will be used to train the data mining algorithms. In our case we use a back-propagation neural network and a decision tree for the data-mining step. After applying the data-mining algorithm, we get patterns to be evaluated in the pattern evaluation step. In the case of the decision tree, our patterns are human understandable as we will show in section 2.3, but the patterns found with the neural network are difficult to interpret because are hidden in the neural network weights and architecture. The patterns found in the training phase will be used in the diagnosis phase shown in figure 5b. The diagnosis starts with the image to be analyzed. We first perform the image preparation filter and then use a segmentation algorithm to find our ROI's (in this case we do not have a marked image) that correspond to possible calcifications. Once we have our ROI's, we execute the feature extraction algorithm to get our feature database, where each ROI is represented by a feature vector. In the next step, we compare each ROI (represented by its feature vector) with the patterns found in the training phase and if the ROI matches any of the positive patterns we diagnose that ROI as positive or a calcification and as negative otherwise.

2.3 Experiments and Results

Data-mining is the task of finding interesting, useful, and novel patterns from databases. In our case we want to find patterns that describe calcifications in mammograms so that we can use them to predict whether a new mammogram has calcifications or not. For this purpose, we use a back-propagation neural network and a decision tree as our data mining algorithms. Neural networks have the property of achieving high accuracies for the classification task but what they learn is not easy to under-

stand. On the other hand, decision trees are known to achieve high accuracies in the classification task and are also easy to understand. For our experiments we find positive and negative regions of interest from 70 mammogram images with calcifications and 60 mammogram images with no calcifications. From these images, we found a total of 649 ROI's, from which 327 were positive (calcifications) and 326 were negative (non calcifications). We performed the feature extraction process to these ROI's and trained our data mining algorithms with them. We used the 10 fold cross validation technique to evaluate the algorithms performance. With the neural networks algorithm we achieved a predictive accuracy of 94.3 % and with decision trees 92.6%. As we can see, we got better results with the neural network algorithm than with the decision tree. The only problem with the neural network results is that they are not easy to understand and we needed to show the learned patterns to our domain expert. This is why we generated rules with the decision tree and asked our domain expert to study them. Dr. Higuero found the rules very interesting and told us that she was relating them to the way she does her diagnosis. Figure 6 shows two of these rules. The first rule says that if the area of the ROI is less or equal to 13, and its diameter is less or equal to 2, then it might not be a calcification. Rule 2 says that if the roundness of the ROI is less than 0.68, and its contour length is greater than 10.49, then it might be a calcification. These rules are obtained from the decision tree by following the path starting at the root node to the leaves.

1) If area <= 13, and diameter <= 2, then calcification = negative
2) If roundness > 0.68, and contour length > 10.49, then calcification = positive

Figure 6. Decision Rules from the Calcification Detection Domain.

Another medical domain that we have been working with is the tuberculosis domain, which is discussed in the following section.

3 Tuberculosis Domain

Since 1993, the world program against Tuberculosis created by the World Health Organization (WHO) took the decision to declare tuberculosis as a "world emergency". A lot of efforts have been focused to get it into control and eradicate it. Although some advances have been achieved with the SSST (Strictly Supervised Shortened Treatment) [2], this year there will be more deaths caused by tuberculosis than any other year in history [3]. According to the WHO with the World Health Report 2002, tuberculosis represents the number eight cause of death in the world, which is even more dangerous than car accidents, breast cancer and bronchial and tracheal diseases. Although we recognize the success in some countries in the fight against tuberculosis, it has not been overcome, even less with its new allied: the AIDS virus. Some of the causes of the tuberculosis problem are due to human factors (as an individual or as a determined group of risk). The Mycrobacterium tuberculosis bacillus, also known as the Kotch bacillus, knows how to protect itself. After thousands of years of evolution it has developed extraordinary surviving strategies. Because of

this, it is very difficult to win a battle against such an enemy with a lot of advantages. This is the reason why we need to use new technologies for a good strategy against the disease. We think that we can find important knowledge to fight tuberculosis from treatment databases and here is where data mining techniques can help us to design a fight strategy against tuberculosis in Tlaxcala so that we can definitely eradicate it.

3.1 Database

The tuberculosis database contains data about the evolution of patients with tuberculosis under treatment. The database consists of 232 cases with information about the patient, the diagnosis, the treatment, and the classification of the case. Patient related data identifies the patient and the place where he was under treatment. Diagnosis data describes laboratory results and the diagnosis method that was used among other information. Treatment information describes how the patient evolved to the treatment, which medication he used, etc. The final classification of the patient shows the treatment length, treatment schema and the class of the patient by the time he finished the treatment. The class can be healthy, non-healthy, death, unfinished treatment, moved to another location, in treatment, or failure.

3.2 Methodology

In this section we explain the steps of the KDD process applied to the tuberculosis domain. In this domain we did not need the image preprocessing steps as we did for the calcifications detection domain. In the first step of the process (development and understanding of the application domain), we studied the tuberculosis disease so that we could understand it. We also invited a domain expert (a doctor who has studied the disease for a long time) to help us to understand the domain and to evaluate the patterns found with the data mining techniques in the database. The domain expert wants to use the discovered knowledge to enforce the prevention and control program to eradicate the tuberculosis disease from Tlaxcala. In the second step (creation of the target data set), we selected a subset of the attributes and examples from the database to use in the KDD process. For our first experiment, we selected all the data of all the registered patients with the tuberculosis disease (that is, we used the whole database). In other experiments we used only data for a specific period of time (months of treatment) in order to find patterns that help us to make suggestions about the treatment process, which lasts for 6 months. In the data preparation step we eliminated noise, discretized some attributes and replaced some null values with a constant. The data transformation phase involved the transformation of information into star graphs, one star graph per case. For the data mining task we chose to use the Subdue algorithm that uses a graph-based representation as described before. For the pattern interpretation and evaluation step we had the participation of our domain expert. He carefully analyzed the patterns found and decided which of them were useful and at the same time contained something important about the data. Finally, in the knowledge consolidation step, we documented the patterns that we considered knowledge (patterns that were novel and useful) and we will try to use them to create a program

that help us to have a better control in the eradication of the tuberculosis disease. It is important to say that some of the steps in the KDD process are not clearly separated. It is possible to go back to a previous step and change a decision taken before in order to enhance the results (KDD is an iterative process). A light modification in one of the steps might strongly affect the rest of the process. The whole process is crucial in order to succeed.

3.3 Experiments and Preliminary Results

As we have not concluded our experiments in the tuberculosis domain, we will only present some preliminary results in this section. For our experiments with Subdue in the Tuberculosis domain we used all the cases (a total of 232) stored in the database. In this experiment we eliminated missing values because if we replaced those missing values with any other value we found that the substructures found were biased by them. Figure 7 shows one of the substructures found by Subdue in the tuberculosis domain. This substructure was found in 156 of 232 cases and is telling us that the 67% of the patients that were under treatment (Treatment = 1) in 2002 (Year = 2002) had lung tuberculosis (Localization = 1) that was diagnosed by the bacillus test (DiagnosisMethod = 1), the patient was found to have tuberculosis in an external consult (DetectionService = 1). The fact that these cases belong to state number 29 (Tlaxcala) is not relevant because all the patients are from Tlaxcala.

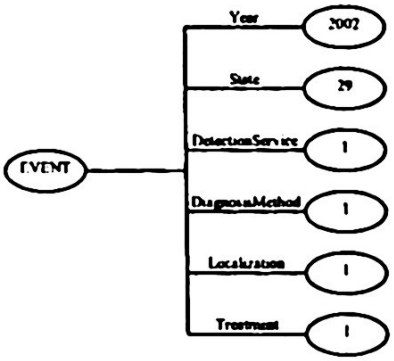

Figure 7. A Substructure Found by Subdue in the Tuberculosis Domain.

We are using the substructures found by Subdue to enhance the methodology used to eradicate the tuberculosis disease. That is, we need to find out what is failing in the process so that we can reduce the number of deaths caused by tuberculosis. This is how the patterns found in this domain are helping the domain expert in this task. We still need to make more experiments with Subdue (including its concept learning version called SubdueCL) and try other algorithms such as decision trees and association rules. We also need to test the predictive accuracy of the patterns found.

4 Conclusions and Future Work

As we could see through this paper, data mining techniques applied to medical domains can really contribute to improve the data analysis capacity to find hidden knowledge from databases. In the case of the calcifications detection in mammograms domain, we were able to find patterns describing calcifications that can be used to detect calcifications in new images with a predictive accuracy of up to 94.3 %. Radiologists can use this method as a second opinion for their diagnosis or to train radiology students. In the case of the tuberculosis domain, we are finding descriptive patterns that are used by the domain expert to study what might be wrong in the current process used to eradicate the tuberculosis disease so that the process can be enhanced. Our future work in the calcifications detection in mammograms domain we want to try different data mining algorithms such as Bayesian networks and also we want to find other characteristics that yield to better results. In the case of the tuberculosis domain, we want to use the association rules and decision trees algorithms to find different patterns and we also want to test the predictive accuracy with the patterns found.

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Optimizing Automatic Classification of Neural Cells

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Abstract. Effective automatic classification of neural cell could be done by using Bayesian decision trees on features extracted from data. Data is normally taken from studies in which the cultures were photographed using a Photonic Science microscope camera. However Bayesian networks are based on a formal assumption that the unconnected nodes are conditionally independent given the states of their parent nodes. This assumption does not necessarily hold in practice and may lead to loss of accuracy. We propose a methodology whereby naïve Bayesian networks are adapted by the addition of hidden nodes to model the data dependencies more accurately. We examined the methodology in a computer vision application to classify and count the neural cell automatically. Our results show that a modified network with two hidden nodes achieved significantly better performance with an average prediction accuracy of 83.9% compared to 59.31% achieved by the original network. In this paper we also justify the improvement of performance by examining the changes in network accuracy using four network accuracy measurements; the Euclidean accuracy, the Cosine accuracy, the Jensen-Shannon accuracy and the MDL score. So that this approach utilized to optimise the automatic classification of neural cell morphology.

1 Introduction

Developmental biologists are frequently interested in classifying the development of cells in culture. In this way they can determine the effects of pollutants (or other reagents) on growth. Oligodendrocytes are a class of cell that is frequently studied. They provide the myelin sheath needed for nervous impulse conduction. Failure of these cells to develop leads to the disease multiple sclerosis. In studies, biologists view culture dishes under a microscope and attempt to count the cells using a small number of classes. This is, however, a difficult, inaccurate and subjective method that could be greatly improved by using computer vision.

Bayesian networks employ both probabilistic reasoning and graphical modelling can be adapted to computer vision. This approach, however, represents the relationships between variables in a given domain based on the assumption of conditional independence [1]. However, in practice the variables may contain a certain degree of dependence and as a result the validity of a network can be questioned. Pearl proposed a star-structure methodology to overcome the dependency problem by introducing a hidden node when any two nodes have strong condi-

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tional dependency given a common parent [1,2]. Pearl's idea was to simulate the common cause between two nodes by introducing a hidden node, though he did not provide a mechanism for determining the parameters of a discrete node. In some cases, hidden nodes can be introduced subjectively through expert knowledge. However, it is rare to have information about common causes that result in variables being partially correlated. It is therefore necessary, in many cases, to use an objective method to introduce a hidden node into a network and estimate statistically the number of states and the link matrices. In neural networks, hidden layers have been widely used to discover symmetries or replicated structures; in particular, Boltzmann machine learning and backward propagation training have been proposed to determine hidden nodes [3].
Friedman proposed a technique called the Model Selection Expectation-Maximization (MS-EM) to update a network by discovering a hidden node. This approach, however, required defining the size of the hidden node prior to its process being carried out [4].

Bang and Gillies extended Kwoh and Gillies' idea [5] by proposing a diagonal propagation method to form a symmetric propagation scheme that compensated for the weakness of forward propagation in the gradient descent process [6]. This method utilized gradient descent to update the conditional probabilities of the matrices linking a hidden node to its parent's and children. Experiments in neural cell morphology showed significant improvement in performance [7]. The results showed that a modified network with two hidden nodes achieved 41.4% improvement in performance.

In this paper, we examine Bayesian networks with the hidden node methodology in terms of the improvement of classification accuracy and network accuracy that can be directly applied to improve the classification accuracy of neural cell morphology.

2 Hidden Node Methodology

2.1 General Concepts

Hidden nodes are introduced to a network (BN_H) by first identifying a triple (A, B, C in Figure 2.1) where the children nodes have a high conditional dependency given some states of the parent node in the original network (BN_O). Once the hidden node is introduced into the network, its states and link matrices are set to make B and C conditionally independent given A (BN_H). This requires the use of a representative data set with values for A, B and C.

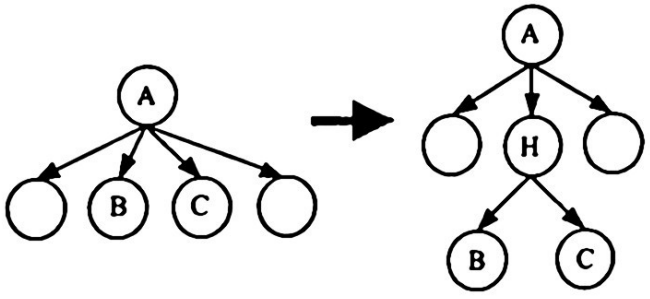


Fig. 2.1. Adding hidden nodes

Having inserted the hidden node H, the three conditional probability matrices (CPTs) linked to the hidden node are initialised. Empirical results showed that the optimal number of states of a hidden node lies between the largest numbers of states among the other nodes (A, B and C) and two times the largest states [6].

To obtain the CPTs, we compute the derivative of the error cost function E with respect to each component of the vector $\vec{p}$ containing all the conditional probabilities. The vector derivative, $\nabla E(\vec{p})$, is called the gradient of E with respect to $\vec{p}$ and denoted as

$$\nabla E(\vec{p}) \equiv \left[\frac{\partial E}{\partial p_1}, \frac{\partial E}{\partial p_2}, \ldots \frac{\partial E}{\partial p_n}\right]. \tag{1}$$

The training rule of gradient descent is given as

$$\vec{p}_i \leftarrow \vec{p}_i + \Delta\vec{p}_i. \tag{2}$$

where $\Delta\vec{p}_i$ is $-\mu\nabla E$, and μ is a positive constant called the step size (or a learning rate) that determines how fast the process converges. For individual probabilities the rule is further expanded to

$$p_i \leftarrow p_i - \mu\left[\frac{\partial E}{\partial p_i}\right]. \tag{3}$$

The objective of gradient descent is to determine iteratively the minimum error:

$$E(\vec{p}) = E_{\min}. \tag{4}$$

or equivalently

$$E'(\vec{p}) = 0. \tag{5}$$

In our case, using backward propagation the error function can be written as

$$E(\vec{p}) = \sum_{data}\sum_{x=1}^{|A|}\left[D(a_x) - P'(a_x)\right]^2. \tag{6}$$

where |A| is the number of values of A, a_x is the x^{th} value, and the vector $\vec{p}$ contains, as its elements, all the unknown conditional probabilities in the link matrices. $P'(a_x)$ is the posterior probability of the parent node A and is calculated by instantiating the children and propagating these values through the hidden node. $D(a_x)$ is the desired value of the parent node originally from the data.

An exact gradient solution is only available in the linear cases. We, therefore, need to expand the equations to derive discrete operating equations.

2.2 Operating Equations for Gradient Descent in Bayesian Networks

The operating equations for gradient descent are derived using the chain rule to differentiate the error function. The equations for diagonal propagation are summarized.

In right-to-left propagation we instantiate root node A and child node C simultaneously. The information from the instantiated nodes propagates through hidden node H until it reaches node B. We need to determine the derivative of the error cost function $E(p)$ with respect to the three link matrix elements. For example consider $\partial E(p)/\partial P(b_j \mid h_t)$. The derivative is expanded using a chain rule as

$$\frac{\partial E(p)}{\partial P(b_j \mid h_t)} = \sum_{y=1}^{|B|}\left[\frac{\partial E(p)}{\partial P'(b_y)}\frac{\partial P'(b_y)}{\partial \pi(b_j)}\frac{\partial \pi(b_j)}{\partial P(b_j \mid h_t)}\right]. \tag{7}$$

The first term on the right side of the above equation is the derivative of the sum of square error cost function $E(p)$ with respect to $P'(b_y)$. Differentiating $E(p)$ with respected to $P'(b_y)$ yields

$$\frac{\partial E(p)}{\partial P'(b_y)} = \sum_{y=1}^{|B|} -2\left[D(b_y) - P'(b_y)\right]. \tag{8}$$

The second term of the equation is the derivative of the posterior probabilities of a target node $P'(b_y)$ with respect to $\pi(b_j)$. Initially the posterior probabilities are denoted as the product of the evidence of the hidden node H and the prior probability distribution of target node B, respectively.

$$P'(b_y) = \beta\lambda(b_y)\pi(b_y) = \beta\pi(b_y). \tag{9}$$

where the normalization factor β is $1\Big/\sum_{y=1}^{|B|}\pi(b_y)$ and $\lambda(b_j)$ has unit values. In the denominator of β the sum is taken over the states of target node B. The derivation of the second term yields

$$\frac{\partial P'(b_y)}{\partial \pi(b_j)} = \beta\frac{\partial \pi(b_y)}{\partial \pi(b_j)} + \pi(b_y)\frac{\partial \beta}{\partial \pi(b_j)}. \tag{10}$$

where $\dfrac{\partial \beta}{\partial \pi(b_j)} = \dfrac{1}{\left[\sum_{y=1}^{|B|}\pi(b_y)\right]^2} = -\beta^2$

The second term is, furthermore, extended with respect to $\pi(b_j)$ for two cases; $j = y$ and $j \neq y$.

$$\beta\delta(j,y) - \pi(b_y)\beta^2 = \beta\left[\delta(j,y) - \beta\pi(b_y)\right]. \tag{11}$$

where $\delta(j,y) = 1$ for $j = y$, 0 otherwise.
The last term is the derivative of $\pi(b_j)$ with respect to $P(b_j \mid h_t)$. Initially we have

$$\pi(b_y) = \sum_{s=1}^{|H|} P(b_y \mid h_s)\pi_b(h_s). \tag{12}$$

$$= \sum_{s=1}^{|H|} P(b_y \mid h_s)\lambda(h_s)\pi(h_s). \tag{13}$$

Then the derivation yields

$$= \sum_{s=1}^{|H|} P(b_y \mid h_s)\lambda(h_s)\pi(h_s). \tag{14}$$

After combing the three terms, we have

$$\frac{\partial E(p)}{\partial P(b_j \mid h_t)} = \sum_{y=1}^{|B|} \left(\sum_{data} -2\left[D(b_y) - P'(b_y)\right] \cdot \sum_{data} \beta\left[\delta(j,y) - \beta\pi(b_y)\right] \cdot \lambda(h_t)\pi(h_t) \right). \tag{15}$$

Other elements are derived similarly as follows

$$\frac{\partial E(p)}{\partial P(c_k \mid h_t)} = \sum_{y=1}^{|B|} \left[\frac{\partial E(p)}{\partial P'(b_y)} \frac{\partial P'(b_y)}{\partial \varepsilon(h_t)} \frac{\partial \varepsilon(h_t)}{\partial \lambda(h_t)} \frac{\partial \lambda(h_t)}{\partial P(c_k \mid h_t)} \right]. \tag{16}$$

$$= \sum_{y=1}^{|B|} \left(\sum_{data} -2\left[D(b_y) - P'(b_y)\right] \cdot \beta P(b_y \mid h_t)^2 \cdot \pi(h_t) \cdot P'(c_k) \right). \tag{17}$$

where ε is a posterior probability of hidden node H.

$$\frac{\partial E(p)}{\partial P(h_t \mid a_i)} = \sum_{y=1}^{|B|} \left[\frac{\partial E(p)}{\partial P'(b_y)} \frac{\partial P'(b_y)}{\partial \varepsilon(h_t)} \frac{\partial \varepsilon(h_t)}{\partial \pi(h_t)} \frac{\partial \pi(h_t)}{\partial P(h_t \mid a_i)} \right]. \tag{18}$$

$$= \sum_{y=1}^{|B|} \left(\sum_{data} -2\left[D(b_y) - P'(b_y)\right] \cdot \beta P(b_y \mid h_t)^2 \cdot \pi(h_t) \cdot P'(c_k) \right). \tag{19}$$

The operating equations for right-to-left propagation are found simply by swapping b and c in the above equations.

3 Case Study: Neural Cell Morphology

Our data was taken from studies in which the cultures were photographed using a Photonic Science microscope camera. Biologists classified the cells in the pictures into four developmental classes. One data set had 12 progenitor cells, 24 immature type 1, 15 immature type 2 and 9 fully differentiated cells. The images were then

processed to extract several features, of which five proved to have good discriminant properties [11]. These were called the Scholl coefficient [12], the fractal dimension [13], the 2nd moment [14], the total length and the profile count.

We conducted a series of tests using the cell class as a hypothesis node, and the five measured features as variables. In particular, we were interested in the possibility of improving the prediction accuracy of the networks with the help of hidden nodes.

3.1 Naïve Bayesian Networks

A naïve Bayesian network was constructed using a randomly selected training data set and then evaluated with a randomly selected test data set. The process was repeated 1000 times for each test. Fig. 3.1.1 shows the naïve Bayesian network with five variables connected to a root node, *neuron type*.

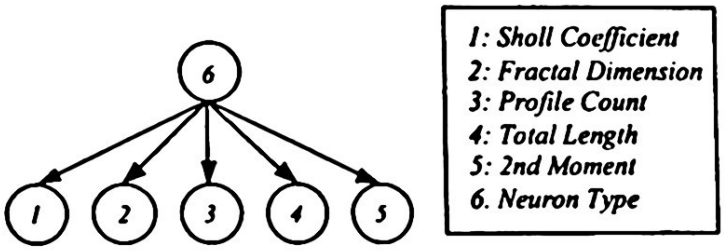


Fig. 3.1.1. A naïve Bayesian network in the morphometric analysis of neural cells

The prediction accuracy of the network was measured in terms of the success ratio (%) of finding the correct answer by comparing the calculated posterior probability of the network with the desired posterior probability in the data. We conducted initial study to decide the ratio of the training data to the test set data. Even though 90/10 performed well, we used 70/30 and 80/20 through out the experiment since 90/10 could yield a biased outcome due to the small number in the test set. After we conducted our series of experiments based on these two ratios, we averaged them to generate the final results. The initial naïve network produced an average prediction accuracy of 59.31%.

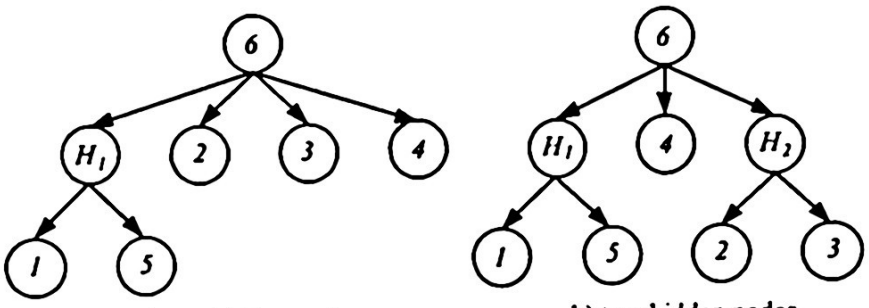
3.2 Training Hidden Node(s)

Based on the results of the conditional dependency measure derived from the mutual information formulae proposed by Chow and Liu [15], we found that the *Sholl Coefficient* and *2nd Moment* showed the strongest conditional dependency (0.731).

We investigated the effect on performance of adding hidden nodes between the different pairs of variables in the network. The places where each hidden node was added are indicated by the node numbers of Fig. 3.1.1. In our experiments we used two different propagation methods for the gradient descent (backwards and forwards (BF), and backwards and diagonals (BLR)). In all cases the performance was found

to improve, and though there was a trend to finding better improvement when placing hidden nodes between the higher correlated variables.

After investigating the single hidden node cases, we tried using a number of structures using two hidden nodes. These were placed at sites where the conditional dependency was high. Examples of the modified network structures are shown in Fig. 3.2.2. The best performance could be achieved by the introduction of two hidden nodes. The addition of two hidden nodes improved the performance to above 83.9% in contrast to the original 59.31%.



a) one hidden node b) two hidden nodes

Fig. 3.2.2. Examples of the structure variations of a naïve Bayesian network with up to two hidden node(s)

4 Network Accuracy

In addition to the prediction accuracy, the Euclidean, the Cosine and the Jensen-Shannon inaccuracy, along with the MDL score are determined for each of the Bayesian networks employed in the experiments. Of particular interest is the improvement in the network accuracy achieved due to the introduction of a hidden node.

Figure 4.1 illustrates the improvement in prediction accuracy (far left of each case) and the improvement in network accuracy, for five single hidden node cases. For example, case *126* represents the case when a hidden node is introduced between node index 1 and 2 given root node 6.

The experimental results demonstrate that the introduction of a hidden node consistently improves the network accuracy. This is due to the proper training of the hidden node, which results in a modified Bayesian network that does not violate the independence assumptions to such an extreme degree as the original Bayesian network.

Furthermore, the experimental results indicate the existence of a correlation between the improvement in network accuracy and the improvement in prediction accuracy. This seems to indicate that indeed the improvement in network accuracy contributes to the improvement in prediction accuracy.

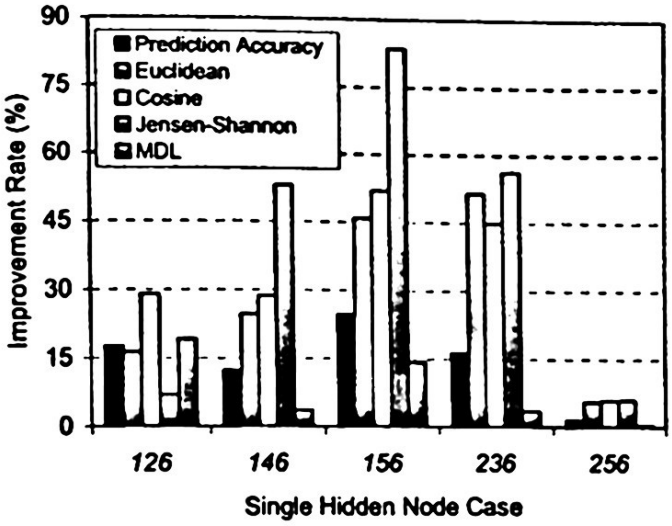


Figure 4.1 Comparison between improvement in prediction accuracy and improvement in network accuracy, in single hidden node cases.

5 Discussion and Conclusion

This study demonstrated that a computer vision application to successfully classify and count the neural cell automatically could be achieved with Bayesian networks with hidden nodes. The improvement in performance is due to the reduction of conditional dependence. Generally it was found that measuring the conditional dependence of two nodes given their parents provided an effective way of deciding where to place the hidden node. The data set that we used did contain a high degree of correlation between the variables allowing for potential improvement through the use of hidden nodes.

The methodology has the advantage of starting from a naïve structure where causal information is as simple as possible, and there is great potential for identifying variables that are related through a common cause or hidden variable. This allows great flexibility in identifying structural changes to the network. The methodology has two further advantages. Firstly the resulting classifier is always tree structured, and therefore fast and efficient to use in practice. Secondly, the performance is guaranteed to be equal or better than the original network, since the three new link matrices, associated with the hidden node, can encode all the information of the original link matrix joining the two children to the parent.

In addition, the experimental results demonstrate the improvement of network accuracy due to the introduction of a hidden node and its proper training. Furthermore, the experimental results indicate the existence of a correlation between the improvement in network accuracy and the improvement in prediction accuracy. Thus, we have provided an experimental justification to the empirically observed improvement in prediction accuracy when employing the hidden node methodology.

Acknowledgement

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Usefulness of Solution Algorithms of the Traveling Salesman Problem in the Typing of Biological Sequences in a Clinical Laboratory Setting

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Abstract. Our concern is to solve the problem of the typing of deoxyribonucleic acid (DNA) sequences in a laboratory setting. Here we try to find solution algorithms for the classification of restriction patterns, which forms part of the above-mentioned problem, in order to evaluate the amount of information generated by a given restriction enzyme. A distance matrix is generated by comparison of each restriction pattern and used to classify the patterns according to their similarity. This problem can be mapped to the Traveling Salesman Problem (TSP). Several known and new solution algorithms have been tested. Interestingly, a very simple and modified nearest neighbor analysis performed best for this kind of problem. However, when the distance matrix is replaced by a "distinction matrix" (expressing directly with the help of a threshold function the similarity (0) or dissimilarity (1) between restriction patterns) the complexity of the problem was reduced dramatically and it could now be solved easily after transitive closure.

1 Introduction

For the TSP, we are given a complete, weighted graph and we want to find a tour (a cycle through all the vertices) of minimum weight [1]. One formal definition of the TSP can be found in [2]. Interestingly, several problems arising from the analysis of DNA sequences can be formulated analogous to the TSP, one of which will be presented and analyzed herein.

DNA is the deoxyribonucleic acid, i.e. the genetic material that encodes the characteristics of living things DNA consists of strings of molecules called nucleotides. There are four nucleotides in DNA distinguished by its base, each denoted by the first letter of the base: adenine (A), cytosine (C), guanine (G) and thymine (T) [3]. A DNA sequence can, therefore, be treated as a character string using an alphabet of 4 letters. The sequence of these letters defines the characteristics of any living being, thus the

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knowledge of the sequence or at least part of it allows the identification of the organism to which the sequence belongs. Thus different types of sequence analysis can be employed in a clinical laboratory setting in order to identify an infectious agent present in a sample taken from a given patient. The instance that will be treated is an example of the so-called sequence-typing problem (STP) applied to the case of the Human Papilloma Viruses (HPV), which is associated with the development of cervical cancer [4]. The required sequence analysis may be performed by a technique called RFLP-PCR (Restriction Fragment Length Polymorphism coupled to Polymerase Chain Reaction). Briefly a segment of the viral genome is analyzed with the help of so-called restriction enzymes, which cut the segment where a small substring is located, i.e. the enzyme EcoRI recognizes the substring GAATTC [5]. The pattern (sizes) of the generated fragments is then determined as it is obviously a function of the sequence itself. The HPV types may then be identified, as long as the corresponding patterns generated by an enzyme are different for each virus. Otherwise, combinations of enzymes have to be used. Until now 48 reference sequences have been published and more than 180 restriction enzymes are available to perform the typing, each recognizing a different subsequence or substring.

In order to select an optimal combination of enzymes to carry out the typing, it is important to evaluate each enzyme, i.e. how much information is yielded on average by the enzyme. This requires in a simple approach to group the restriction patterns according to their similarity, which means that we have to determine the distance between each pair of them and order them linearly according to their similarity. This in turn yields a distance matrix from which we have to select a Hamiltonian path or circuit of minimal weight. Thus, we are confronted with a problem similar to the TSP. The instances are symmetric but not always geometric. However, due to the evolutionary relationship of the viruses, the instances may no behave like random symmetric, non-geometric instances. Furthermore, while a TSP requires the construction of a Hamiltonian cycle, the STP requires finding an optimal Hamiltonian path (restriction patterns ordered linearly according to their similarity). Therefore, although there have been several algorithms published in order to find exact or approximate solutions of the TSP [6], due to the evolutionary relationship between the members it is important to test the behavior of the published and novel hybrid algorithms on these instances. We have not yet analyzed or characterized further the postulated special characteristics of the phylogenetic structure of the TSP.

We started by building a software tool for solving the TSP [7]. This tool has eight solution algorithms; in which five of them are approximate and the other three exact methods. A restricted version of the implementation is accessible online [8]. As almost all algorithms previously implemented in our tool are searching for Hamiltonian cycles, we adapted them to the STP by removing from the solution (a cycle) the edge of maximum weight. As indicated, we evaluated also the usefulness of hybridizing algorithms. We, therefore, constructed and tested two hybrid methods combining initial path with local search algorithms. One of them has already been presented in a previous article [9]. All algorithms are presented briefly in the following section.

2 Methods

Approximate algorithms are a class of algorithms, which do not guarantee optimal solutions but warrant a bound worst-case performance (near to the optimal solution) and run faster than any algorithm that achieves optimality. Subsequently, we describe the approximate algorithms studied in this article.

2.1 2Opt

This solution technique is also called "Two Opt" the short name "Two Optimal", also "Double Option". This technique is one of the most successful heuristic to obtain the approximate solution of the TSP. The Two Optimal Technique is fully described in [10], [11].

2.2 Adaptation-Prim-2Opt-Hybrid method

We modified Prim's algorithm for the minimum spanning tree problem in order to generate an initial path, which was used by the local search 2Opt algorithm in order to optimize the path [9].

A spanning tree is a tree that comprises all the nodes of a given graph and not any more [8]. Greedy algorithms for optimization problems consist of making choices in sequence such that each individual choice is best according to some limited "short term" criterion, which is relatively easy to evaluate. Once a choice is made, it cannot be undone; even if it becomes evident later that it was a poor choice. Although in general greedy strategies don't always lead to optimal solutions or aren't always efficient, Prim's greedy strategy for the minimum spanning tree problem always produces optimum solutions efficiently [1].

Prim's algorithm begins at an arbitrary start vertex and grows a tree from there. During each of the iterations of the main loop an edge is chosen from a tree vertex to a fringe vertex; it "greedily" chooses such an edge with minimum weight [1]. Prim's algorithm produces a minimum spanning tree T; it means an undirected graph with weighted edges. The method is fully described in [9], [10].

In the Adaptation-Prim-2Opt-Hybrid method, Prim's algorithm has been modified such that the result is not a tree but a path. It is another greedy strategy, which has been described previously. Once the path is found, the first and the last node are linked in order to obtain a Hamiltonian cycle (this step is called Adaptation-Prim APRIM), which was fed into the 2Opt method that tries to improve this initial cycle (second step). Both steps joined are called Adaptation-Prim-2Opt-Hybrid method (P2OH).

2.3 MST-2Opt Hybrid method

The problem of determining an optimal tour in the symmetric n city TSP (with a symmetric cost matrix) can be viewed as the problem of finding a minimum cost Hamiltonian cycle in a weighted, undirected graph. With this point in mind it is easy to see that the problem of determining the existence of a Hamiltonian cycle in a complete undirected graph G = (V, E), which is transformable to the symmetric TSP [12].

The following algorithm computes a route close to the optimum of an undirected graph G, using the Minimum-Spanning-Tree algorithm of Prim. Observe that the cost function has to satisfy the inequality of the triangle. In this case the given route found by this algorithm is in the worst case twice as big as the optimal route [12], [13], [14].

The solution algorithm MST-2Opt Hybrid (M2OH) is described below. We have a set (G, c), where G is a complete graph, with a non-negative cost "c".

1. Select any vertex "r" of V [G], which will be the "root" vertex.
2. Compute a minimum spanning tree T for G from a root "r" using the minimum spanning algorithm of Prim: T = (G, c, r).
3. Evaluate L as a list of visited vertices in a walk of a general tree in preorder of T.
4. Link the first and the last node in order to close the path, which will create a Hamiltonian cycle H. This closed path visits all the vertices in the L order.
5. The route obtained from all the vertices of the L list, is transformed in the initial route for the 2Opt algorithm. These five steps form the M2OH.

The execution time of the M2OH is of the order $\Theta(E) = \Theta(V2)$ since the input is a complete graph [13].

2.4 Nearest-Neighbor Adaptation

The Nearest-Neighbor Adaptation (NNA) is a modification of the simple nearest neighbor algorithm [15]. The modification consists in selecting as a specific starting node the one, which has on average the largest distance from the rest of the vertices. From this node we take the nearest neighbor, which hasn't yet been visited, yielding an algorithm with voracious characteristics [15].

2.5 Lin-Kernighan

The heuristics of Lin and Kernighan (LKH) [16] is considered one of the best approximation algorithms of the TSP problem, yielding surprisingly often, optimal solutions for small instances. Briefly, the algorithm uses a flexible n-Opt strategy, where the number n of edge exchanges is determined dynamically at each iteration considering some sort of limiting criterion. We used in our study the implementation of Heldsgaun [17].

2.6 A Better Branch and Bound

This method is based on a search tree where in each step all possible solutions are partitioned in two subsets, one representing all nodes of the remaining search space containing a selected node and the other containing all nodes of the remaining search space without that particular node. Once the ramification has been carried out the bounds for each subset are calculated and the one of the least bound is chosen to continue the search. The particular node picked for the next ramification according to a heuristic that is intended to prune the tree as much as possible. This process is repeated recursively until the Hamiltonian circuit is found [7], [18].

3 Experiments and Results

TSPLIB is a library of sample instances for the TSP that can be used in order to assess the efficiency of algorithms [19]. However, as our goal is not to test the behavior of the algorithms but to analyze their usefulness within the sequence typing problem, we selected a sample of 48 HPV sequence types corresponding to a genomic segment of the L1 gene, which were studied by restriction analysis with 182 restriction enzymes. Only 138 restriction enzymes cut at least one HPV sequence.

In addition, in order to increase the sample size, we performed a restriction analysis with "synthetic" enzymes recognizing all 4-tuples missing from the above mentioned natural set of recognition sequences. We obtained an additional set of 120 instances.

The theoretical restriction patterns were compared with each other. As a measurement of the similarity we used the sum of differences between the migration positions. The matrices showed various degrees of redundancy due to the existence of identical restriction patterns, thus we eliminated the linearly dependent vectors, and some matrices were reduced down to 2x2 matrices. We analyzed only matrices of 3x3 and larger. The distribution of instances is shown in Fig. 1. Later on, we grouped the instances according to the following ranges: 3-9 (10), 10-19 (20), 20-29 (30), 30-39 (40), and 40-48 (50).

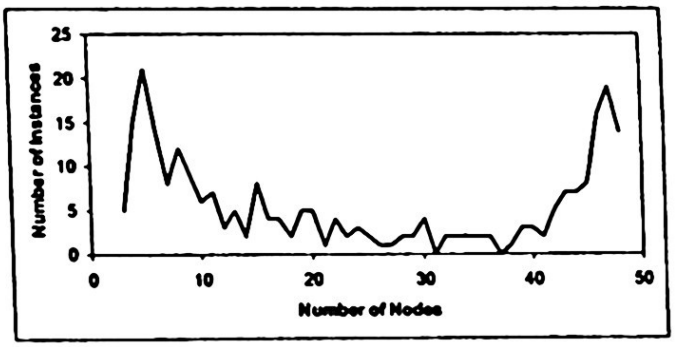
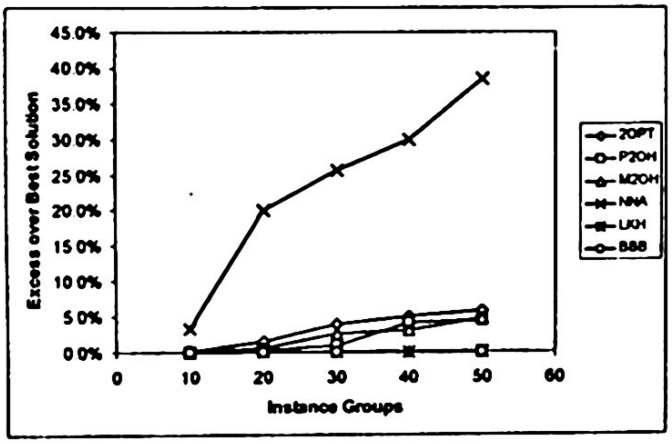


Fig. 1. Size distribution of the instances. We show the total distribution comprising natural as well as "synthetic" enzymes

The matrices were symmetric but frequently not geometric (only 30 out of 259 comply with the triangle's inequality). As the execution times were too short, (less than a millisecond, with the obvious exception of the BBB), the methods were compared by the weight of the Hamiltonian path and cycle. Each instance was analyzed by the mentioned methods, and the result was expressed as the percentage above the shortest path or cycle. We then calculated the average of the above-mentioned ranges. These results are shown in Fig. 2.

A



B

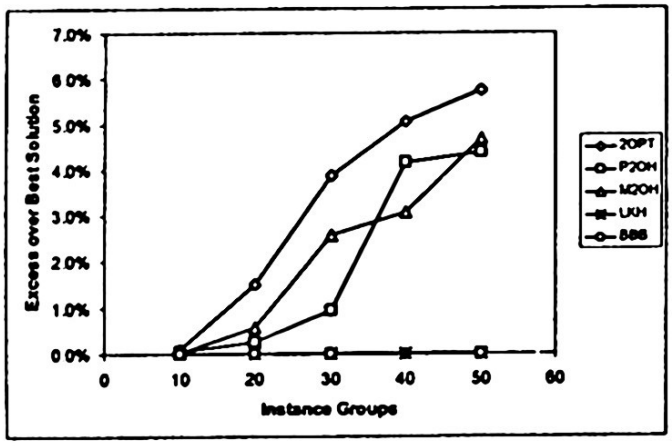


Fig. 2. Hamiltonian cycles. (A) Comparison of the 2OPT, P2OH, M2OH, NNA, LKH, and BBB algorithms. (B) For a better resolution of the results we eliminated the NNA method

As we can see, in Fig. 2 the various methods behave as expected, i.e. the initial path algorithm yields only good solutions for very short instances. All local search algorithms produce better approximate solutions. However, as the instances grow, they deviate stronger from the optimal solution with the exception of the Lin-Kernighan algorithm, which found almost always, optimal solutions. The hybrid methods work better than the local search method by itself.

In Fig. 3 we show the results for Hamiltonian paths. As almost all algorithms previously implemented in our tool are searching for Hamiltonian cycles, we adapted them to Hamiltonian paths by removing from the cycle the edge of maximum weight.

NNA shows a very good behavior with tiny instances; however, its efficiency decreases rapidly with instances above 20 nodes. With the analyzed instances, all other algorithms show a similar behavior. There is only a small but noticeable success of the BBB and LKH for instances larger than 30.

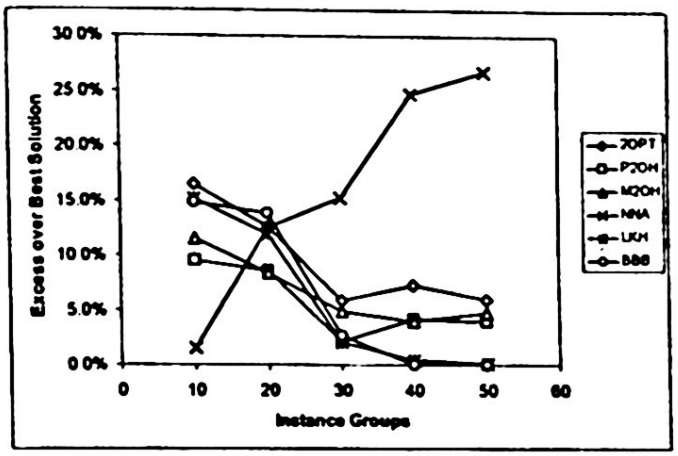


Fig. 3. Hamiltonian paths. Comparison of the 2OPT, P2OH, M2OH, NNA, LKH, and BBB algorithms

Once the restriction patterns have been ordered according to their similarity (either as a Hamiltonian circuit or path), we can now proceed to group them by means of a threshold function in classes of restriction patterns. The number and size distribution of the classes created by an enzyme is related to the information provided. The more groups are formed, the more information may be provided. However, at a given threshold, the less groups are formed the more striking differences between the classes of restriction patterns are emphasized. We analyzed, therefore, the formations of pattern classes and calculated the number of classes formed in excess over the best solution (see Fig. 4).

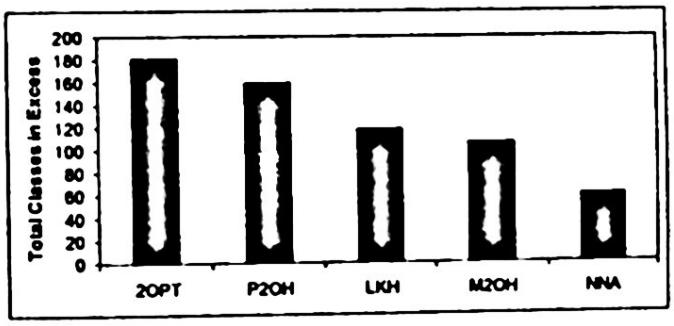


Fig. 4. Number of excess classes. Comparison of the 2OPT, P2OH, M2OH and NNA algorithms

First of all it should be noted that there was no difference in the use of either circuits or paths for the generation of classes, most likely due to the fact that the heaviest

edge, which has been removed from the circuit to generate a path, is always a border between two pattern classes. It has been hypothesized that by optimizing a Hamiltonian circuit based on a distance matrix, the transitions from one pattern to the next are smoothed out so that the number of pattern classes is reduced simultaneously. However, from the Fig. 4 it is apparent that these two events of optimization are not related: the algorithm that yields the worst result in generating circuits forms the smallest number of excess classes. The failure to optimize the number of classes resides in the fact that the target to be optimized is not directly represented by the matrix underlying the TSP. Therefore, we generated with the help of our threshold function a so called distinction matrix, where we report whether two restriction patterns are either similar (0) or belong to different classes (1). This procedure reduced drastically the complexity of the problem and it could now be solved easily by reducing the matrix after its transitive closure (i.e. if $d_{ij} = 0$ and $d_{jk} = 0$, then it must also be $d_{ik} = 0$ for the distances d between any combination i, j, k of three patterns).

4 Discussion and Conclusions

We have analyzed the behavior of several methods for approximate solutions of the TSP and a classification problem applied to our viral instances. As most of the methods have been developed to construct a Hamiltonian circuit, in our first series of experiments we analyzed how good they behave in finding them. As was to be anticipated, initial path algorithms do not perform well in comparison to the implemented local search or combined initial path and local search algorithms. According to our results the most efficient algorithm was the LKH, especially for larger instances. However, by solving the related TSP we could not optimize the classification problem. Nevertheless, the representation of the classification problem as a distinction matrix allowed us to reduce significantly the complexity of the problem and solve it after transitive closure by a simple reduction of the distinction matrices. However, it is worthwhile to note that the restriction patterns ordered by LKH serve as a better template to identify by visual comparison a given pattern obtained from a patient, thus the solution of the underlying TSP may still prove useful.

We have still to test whether there is a significant difference in the complexity of matrices derived from sequences of phylogenetically related organisms or generated at random.

In conclusion, we have demonstrated that in our case even simple traveling salesman heuristics are highly useful to address part of the sequence-typing problem.

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Functional Anatomy of Stereopsis: Effective Connectivity identified using NARMAX and fMRI data

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Abstract. Functional magnetic resonance imaging was used to investigate the relationship between stereo and motion visual processing. Red/green random dot anaglyph stereograms with radial motion were used as visual stimuli. Three main areas of cortical activations were identified. One was sensitive to motion corresponding to V5, one sensitive to sterosis (V5a) and one more responsive to both stimuli (V5+). Time series from the activated regions were extracted from the raw data. Non linear system identification techniques were used to identify a model of the interregional connectivity. The statistical validity of the functional relationship between the different regions was assessed using Structural Equation Modelling.

1 Introduction

Although many psychophysical studies have investigated how the human brain computes stereoscopic information [14],[3], it is quite uncertain which cortical areas are involved in its implementation. Some electrophysiological studies in monkeys report the sensitivity of V1 to absolute disparities, suggesting that this area could be a preliminary stage of processing for stereo information [7]. MT/V5 in monkeys shows a columnar organization tuned for disparity [8]. MT/V5 in human brains has been widely reported as a motion sensitive area [13],[4],[17],[12].

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Given the similarity between the visual system of the monkey and the human [10], it is not unreasonable to think that V5 in human brains is involved in the processing of stereo information as well. However some studies of patients with lesion in parieto –temporal / occipito-temporal (V5) region reported no loss of performance in a stereoscopic depth task [18],[16],[19]. This could be attributed either V5 is not related to stereo disparities processing or there is another region (beyond V5) more sharply tuned to stereoscopic information. The goal of the present study is not only to investigate the cortical areas involved in the processing of stereo information but also how these areas interact with the V5 region.

Functional magnetic resonance imaging (fMRI) is a non-invasive technique that provides the opportunity to monitor activity in time from many regions in the brain. Connectionist approach permits us to use these time series to determine modulatory interactions between connected regions. McIntosh *et all* [11] have demonstrated the use of path analysis to interpret fMRI data in order to assess the validity of models of effective connectivity [9].

Generally speaking these analyses have been done considering only linear relationships among regions however many neuronal interactions are non linear and is important to identify them. In the present study we used a non-linear system identification algorithm (NARMAX) which combines structure selection and parameter estimation. The NARMAX algorithm has been successfully used in many engineering applications due to its facility to capture in few terms the non-linear dynamic of the systems [1].

Structural Equation Modelling (SEM) is a mathematical technique used to assess models that define relations among variables [2]. Although SEM theory is not new, the application of this tool to estimate effective connectivity in the brain is relatively novel [11]. The basic idea of SEM is to test how well a proposed model fits the data observed, this evaluation is given in terms of covariance analysis i.e. the degree to which the activities of two regions are related. The goodness of the model is given by the chi-square statistic (χ^2). SEM was used in this study to evaluate how well the proposed model fits the observed data. A short description of the basic ideas underlying path analysis used in this work was included in an appendix.

2 Methods

2.1 Subjects

Seven healthy right-handed volunteers (4 female,3 male) aged from 20 to 30 years participated in the present preliminary study. One of the male subjects was scanned twice. All subjects gave informed written consent.

2.2 Experiment Design

All subjects did 4 sequential scans each lasting 6 min. 12 sec. (17 epoch) with a 5 min interscan interval to permit subjects to rest. One hundred and twenty four image volumes were acquired in each run. Each condition lasted 21 sec., giving 7 multislice volumes per condition (TR=3 sec.). A dummy condition of a blank screen was presented during the first 15 sec (5 scans) of each run to eliminate magnetic saturation. To avoid habituation the conditions were counterbalanced using a Latin Squares design. The motion stimulus was radial to facilitate fixation following by Buchel's experiments [5],[6]. The subjects were no trained and during all conditions they were instructed to fixate a point (0.3 °) in the middle of the screen (circular field of view 13 °) and foveate among one of the following visual stimuli:

Fixation : In this condition only the fixation point is displayed in the centre of the active area, this condition was taken as a base line. *Stationary*: two hundred and fifty dots (with radio 0.1 °) were randomly positioned within the circular field of view (mean dot density 8 dot deg^{-2} at the centre and 1 dot deg^{-2} in the edges) , the aim of this condition was to activate the visual cortex areas sensitive to the luminance produced by the dots. *Motion*: the same set of dots moving (constant speed 6.8 deg s^{-1}) radially, changing from expansion to contraction every 3 seconds. The dot density was maintained constant by replacing each dot moving outside the visual field with one appearing at the centre. With this stimulus we expected to activate the motion sensitive regions. *Stereo*: the same number of dots positioned in depth (red/green anaglyph stereogram) forming a 3D cone structure (maximum disparity ±0.08 deg.). A 3D cone shape was used to provide a wide range of disparities to stimulate binocular neurons. *StereoMotion*: the previously *Stereo* and *Motion* stimuli were combined.

2.3 Stimulus Presentation

Subjects lay on their back in the magnet. They wore red/green anaglyph glasses and looked via a mirror angled at ~45° from their visual axes at a back illuminated screen located at the extremity of the magnet. The viewing distance was 2.4 m. Stimuli were projected on to the screen using an EPSON (EMP-7300) projector driven by a 3G Mac running Psychophysics Tool Box ver. 2.44 [5],[15] under MATLAB ver. 5.3. The mean luminance of the image was 2.15 cd/m^2. Although the stimuli were displayed at a video frame rate of 60 Hz, the image was only updated on alternate frames, producing an effective frame rate of 6 Hz.

2.4 Data Acquisition

Subjects were scanned in a 1.5 T whole-body MRI scanner (Eclips Marconi Systems) with BOLD contrast echo planar imaging (TR= 3s, TE= 40 ms, 128 x128 voxel, voxel size 1.875 x 1.875 x 4 mm.). Eighteen slices covering the whole visual cortex were acquired.

2.5 Data Analysis

The data was pre-processed and analysed using SPM99 (Welcome Department of Cognitive Neurology). The first five scans of each run were discarded to exclude magnet saturation artefacts. All volumes were slice timed, motion corrected and normalised in the Talairach stereotactic space. The data were smoothed using a 6 mm FWHM (full width at half maximum) isotropic Gaussian kernel . Data analysis was performed using a boxcar design matrix of the different conditions (fixation, stationary, motion, stereo and stereomotion) convolved with the haemodynamic response function. Specific effects were tested by applying the corresponding linear contrast to the parameters obtained applying General Linear Model (GLM) using the design matrix previously described. The statistical parametric maps (SPMs) were then interpreted by referring to the probabilistic behaviour of Gaussian random fields. The threshold adopted was $P < 0.05$ (corrected).

3 Statistical Analysis

Five analyses were performed in order to identify the areas involved in each particular stimulus. In contrast with the consistent and significant activation (V5 region) among subjects following the motion condition, only three subjects showed a consistent activation during stereo. We attribute this to the fact that some people have difficulty persiving stereograms and the activation produced by the stimuli is not strong enough to be significant in the analysis. For reasons of space we show only the regions of activation found in the best subject (fig. 1).

Motion against Stationary: In accordance with previous research the V5 complex area showed the highest activation to the directional motion presented in the stimulus. *Stereo against Stationary:* Much of the cortical tissue sensitive to motion was also sensitive to stereo stimulation, and it is important to note that this contrast reveals some areas that were not activated by the motion stimulus. *Motion against Stereo:* This contrast shows the region (V5 region, Talairach space (45, ±65, -3)), which had higher activation to motion than to stereo. *Stereo against Motion:* The cortical area which was more sensitive to stereo than motion was very small but consistent among three subjects. We could not find in the literature any report of an area with the characteristics shown on this location. We called this area V5a (Talairach space (35, ±83, -3)).

StereoMotion against Motion and Stereo: Given that some regions are sensitive to both stimuli, we used this contrast to assess which areas become more active when both stimuli are presented at the same time instead of when they were presented separately.

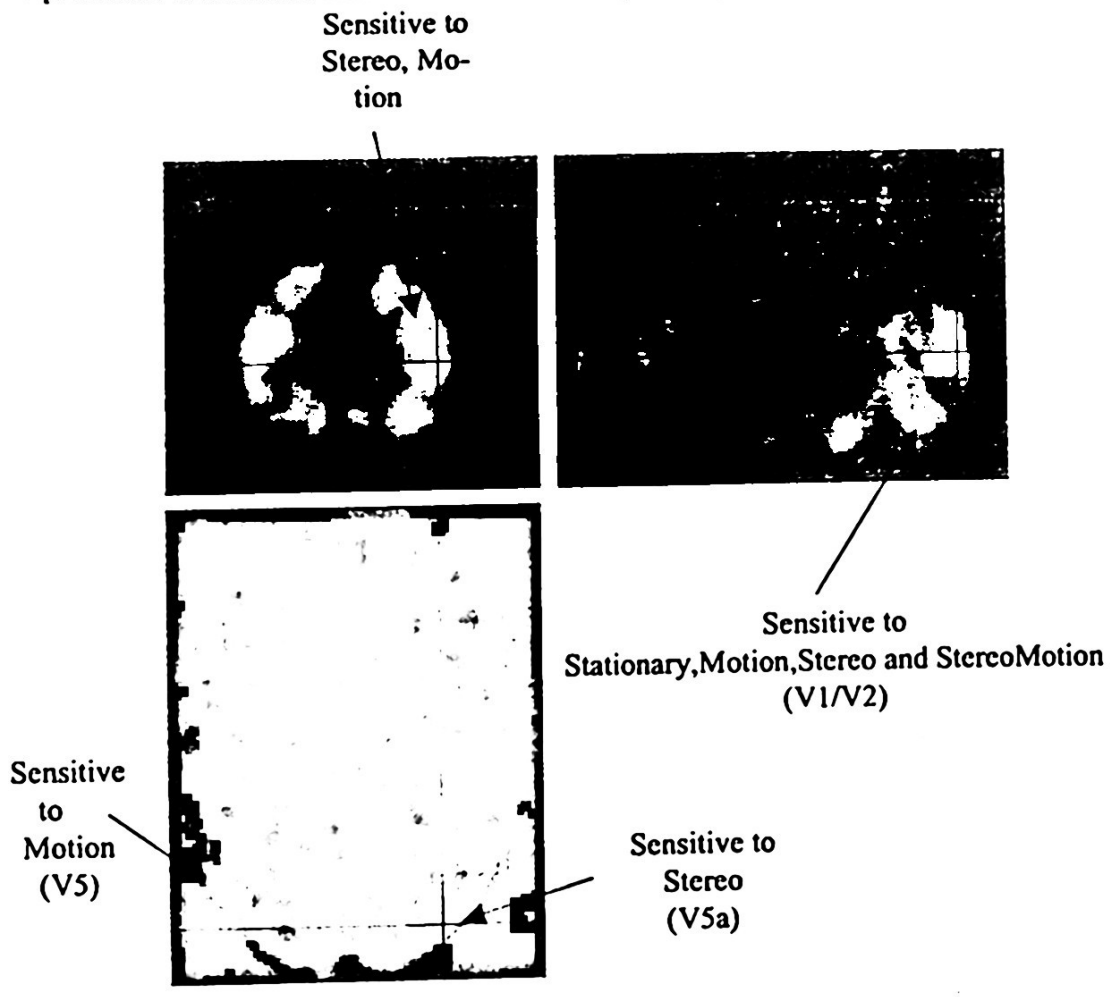

Figure 1. Axial, sagittal and coronal views of slice z=-3 according Talairach space. As we can appreciate V5 and V5a are specifically responsive to motion and stereo respectively. Otherwise V5+ is sensitive to both stimuli.

4 Effective Connectivity Analysis

Our results showed one area in the visual cortex which was both activated by the motion stimulus as well as by the stereo stimulus. We refer to this area as a V5+ (Talairach space (33, -88, 17)).

The mean time series of this region was highly correlated with the boxcar time series of stereo and motion conditions. It is not unreasonable to hypothesise that this area is an early stage of processing of motion and stereo information and that some more specialised areas are necessary to make a further treatment of the respective stimuli. Considering the correlation of the region with the individual models of motion and stereo, we believed that V5 could be a good candidate to realise the specialised processing to motion information and V5a could be the primary place in the processing of stereo information. In order to asses this hypothesis of effective connectivity [Friston, 1994], path analysis (see appendix) was done using the time series from the regions involved.

First, we applied the NARMAX algorithm to identify the interaction terms (i.e. non linear relationships) among regions. Some apriori constraints were introduced as an anatomical connection between regions. An interactive term (V5xV5a) was suggested by NARMAX to explain the response activation of the joint activity of V5 and V5a. The statistical significance of the model was evaluated applying SEM. The Analysis of Moment Structures (AMOS ver. 4) software package was used in this analysis. As an indicator of correctness, the probability level achieved was near to one (fig. 2).

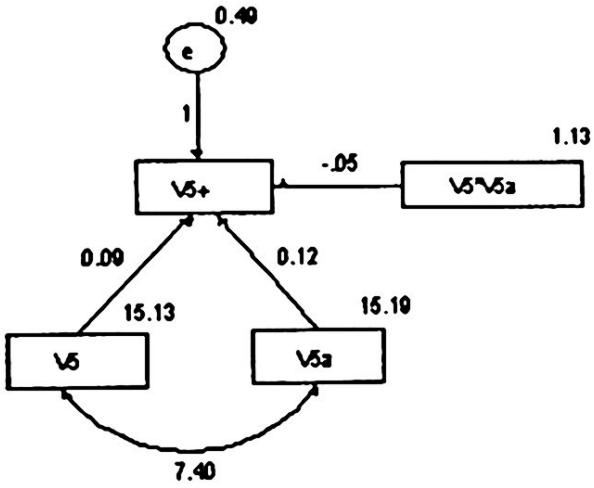

Figure 2. The model following the use of NARMAX algorithm was assessed using AMOS 4.01 SEM software. The covariance analysis with 2 degrees of freedom achieved a chi-Square = 0 and a probability level of 0.99, implying that the model is a very good fit of the data.

5 Conclusions

A conclusion of our research is that area V5 in humans appears to be functionally similar to MT in monkeys, not only in the sense that both of them process motion information, but also because both are involved in the processing of stereo disparities.

Our results suggest that V5 complex has a specific set of neurons tuned exclusively to compute stereo disparities. We called V5a this new functional defined area which is specialised in the treatment of stereoscopic information.

A model of effective connectivity that accounts for the functional architecture of stereoperception was presented. The validity of the proposed model was tested statistically using structural equation modelling. Finally, we believe that the inconsistency in V5a activation among subjects is caused by the large range of people ability to solve stereograms. Owing to all subjects were not trained future work has to be done to explore the effects of training to ensure a good level of stereo acuity between subjects.

6 Appendix: Path Analysis

Path analysis is a mathematical technique which is used to find a model that best explains the causal relationship among the data. Path analysis can be split in two different but complementary procedures, the first one is called *exploratory analysis*, in this stage the objective is to find the structure of the model (system identification problem). The second one, called *confirmatory analysis*, consists of assessing how well the proposed structure fits our data.

6.1 Exploratory Analysis

In order to solve the system identification problem we propose the use of Multi input Multi output Non-linear AutoRegressive Moving Average with eXogenous inputs (MIMO-NARMAX) algorithm [1]. The underlying idea behind this algorithm is to represent the model as linear-in-the-parameters non-linear difference equation system and estimate the parameters doing an orthogonal decomposition. For example, let the dependent variable Y be represented as the following discrete-time multivariable non-linear stochastic system:

$$Y(t)=f(Y(t-1),\ldots,Y(t-n_y),\ U(t-1),\ldots,U(t-n_u),\ E(t-1),\ldots,E(t-n_e))+E(t) \qquad (1)$$

Where Y, U and E represents endogenous, exogenous and error terms respectively with n_y, n_u and n_e maximum lags (memory of the system). Due to each term in (1) represents a family of subterms it can be decomposed in:

$$\begin{aligned} y_i(t) = f_i(&y_1(t-1),\ldots, y_1(t-n_y),\ldots, y_m(t-1),\ldots, y_m(t-n_y),\\ &u_1(t-1),\ldots, u_1(t-n_u),\ldots, u_r(t-1),\ldots, u_r(t-n_u),\\ &e_1(t-1),\ldots, e_1(t-n_e),\ldots, e_m(t-1),\ldots, e_m(t-n_y)) + e_i(t) \end{aligned} \quad (2)$$

The non-linear form of f_i can be approximated by the polynomial expansion of order l ,where multiplicative terms between monomials are calculated and included as new terms of the system:

$$y_i(t) = \theta_0^{(i)} + \sum_{i1=1}^{n} \theta_{i1}^{(i)} x_{i1}(t) + \sum_{i1=1}^{n}\sum_{i2=i1}^{n} \theta_{i1i2}^{(i)} x_{i1}(t)x_{i2}(t) + \ldots + \sum_{i1=1}^{n}\cdots\sum_{il=1}^{n} \theta_{i1\ldots il}^{(i)} x_{i1}(t)\ldots x_{il}(t) + e_i(t) \quad (3)$$

This representation capture the non linearity of the system and is linear in the parameters. The expanded system can be expresed as:

$$y(t) = \sum_{i=1}^{M} p_i(t)\theta_i + e(t) \quad (4)$$

$$Y = P\theta + e \quad (5)$$

Where P represents the full model set (design matrix). The problem of structure selection and parameter estimation can be sorted out finding the subterms P_i of P which minimise *e*. This minimisation can be formulated as a standard least squares problem, however, due to some terms in P are very similar and P^TP easily becomes singular, we used a forward regression orthogonal decomposition (Gram-Schmidt orthogonalization) to estimate the θ_i parameters. The complexity of the system (how many terms include as a predictors) can be controlled using a parsimony criteria like Akaike's information or Bollen's parsimonious fit index.

6.2 Confirmatory Analysis

The use of Structural Equation Modelling as a confirmatory tool implies the existence of a theoretical model proposed to explain the observed data. The hypothesis to assess is that the observed covariance (S) taken from the data is equivalent to the implied covariance ($\Sigma(\theta)$) of the model. The relationships between the variables included in the model are expressed as a structural equations, for example consider the following model that establish the connectivity between three variables A, B and C:

$$B = \theta_1 A + \Psi_2 \quad (6)$$

$$C = \theta_2 A + \theta_3 B + \psi_3 \quad (7)$$

Matrix notation:

Vector notation:

$$\begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ \theta_1 & 0 & 0 \\ \theta_2 & \theta_3 & 0 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} + \begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{bmatrix}$$

$$v = K v + \psi \quad (8)$$

Where v is a vector that represents the observed variables, K is the matrix of coefficients and ψ is a vector of residuals. The positions in K that contain 0 denote the lack of connection between these variables. Factorising (8) we have:

$$v = (I - K)^{-1}\psi \quad (9)$$

Then the implied covariance matrix is constructed following the hypothesis that $S = \Sigma(\theta)$.

$$S = v \bullet v' \quad (10)$$

Then substituting (9) in (10)

$$\Sigma(\theta) = (I - K)^{-1}\psi \, ((I - K)^{-1}\psi)' \quad (11)$$

The estimation of the parameters in θ that minimise the difference between S and $\Sigma(\theta)$ is usually done using the maximum likelihood description function (ML) that is asymptotically distributed as chi-square statistic. The goodness of fit of the model can be estimated using χ^2 distribution with degrees of freedom equal to the number of non repeated terms in the observed covariance matrix minus the number of parameters to be estimated in the model.

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Coordinating Distributed CLP-Solvers in Medical Appointment Scheduling*

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Abstract. Research on monolithic logic-based systems has usually left out an important aspect of information technology systems supporting medical processes — distribution. Often social restrictions build up by questions of authority prohibit the implementation of global systems with omniscient view. Hence, IT in medical domains has to obey these restrictions by being distributed as well. The direct consequence is the need for communication and coordination. In this paper, we present an industrial-size case study in medical appointment scheduling that is envisaged to be solved by combining the strength of CLP for local (internal) problems with the strength of coordination for external problems. The essence of this approach is the realization of a multi agent system (MAS) consisting of CLP-based agents.

1 Introduction

Applications of information technology in medical domains are confronted with at least two aspects. The first aspect is the support of complex decisions in diagnosis, therapy and administration. Usually, these decisions include some kind of planning, scheduling or reasoning on expert knowledge. Research on Artificial Intelligence has made many successful contributions to these fields in general by introducing action planning, intelligent scheduling and expert systems. Logic Programming and Constraint Logic Programming (CLP) are among the most influential paradigms in this context. Nevertheless, research on monolithic logic-based systems has usually left out the second important aspect of information technology in medicine — distribution.

Almost all medical processes are distributed spatially and among several individuals. Social restrictions build up by questions of authority prohibit the implementation of global systems with omniscient view. Hence, IT in medical domains has to obey these restrictions by being distributed as well. The direct consequence is the need for communication and coordination. The notion of an *intelligent agent* [10, 11] is a recent concept that tries to incorporate the

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merits of sophisticated AI methods with strong communication and interaction capabilities.

In this paper, we present an industrial-size case study in medical appointment scheduling that is envisaged to be solved by combining the strength of CLP for local (internal) problems with the strength of coordination for external problems. The essence of this approach is the realization of a multi agent system (MAS) consisting of CLP-based agents. After describing the case study, our general strategies and the given variables and constraints in section 2, we focus on the coordination of distributed CLP solving in section 3. Discussion of related work and prospects conclude this article.

2 Medical appointment scheduling

2.1 Case study — ChariTime

CLP and intelligent agents have traditionally been applied to the control and optimization of industrial transport and production processes. In contrast to that, our research is more involved with human processes in the domain of administration and health care management. Several researchers from GMD FIRST, Humboldt University Berlin and Technical University Berlin are currently carrying out a case study at the cardiological clinic of Charité Berlin, Europe's biggest hospital. The cardiological clinic of Charité consists of five wards with a capacity of altogether over 80 patients, four outpatients' facilities, in which different types of medical consulting are done in parallel, and eight diagnostic units, some of which with several workplaces. The diagnostic units perform over 100 diagnostic examinations each day. These examinations are requested by the wards, the outpatients' department and other clinics of Charité.

The present problem is the coordination between the requesting and serving units. Spatial and organizational distribution of the named units results in distributed knowledge, distributed control and hence suboptimal patient throughput and resource usage. Traditional monolithic systems often scale purely in measure of process instantiations and they usually ignore the problem of restricted information distribution. Therefore, a more local and flexible architecture is needed to control the requesting and serving processes in diagnosis.

We have decided to design and realize a truly distributed multi agent system which will (hopefully) run on 25 to 30 computers all over the whole cardiological clinic. This system is called ChariTime. It shall be permanently active to allow the dynamic allocation of actors and resources to diagnostic tasks, while coping with failures and emergency cases. We have modeled the given problem as a coordinated problem solving task among autonomous but benevolent agents.

2.2 General strategies

A usual problem of socially embedded IT systems is acceptance. The introduction of IT is often a management decision as it is in our case. Especially

scheduling appointments automatically can have major impact on every day's work. Therefore, in ChariTime we have introduced a variety of properties that can be adjusted by the users and influence the way in which the system schedules appointments.

A key property is the possibility to restrict the number of fixed appointments for every type of examination for each day. Fixed appointments are preferably given to outpatients. Fixed appointments that are not used for outpatients are given to ward patients. Ward patients that have not been assigned a fixed appointment are registered in a priority queue that can be used by the diagnostic unit to flexibly fill the time between fixed appointments.

Appointment relocation is very common in medical appointment scheduling. The request for an appointment is not only prioritized by a basic patient priority but also by medical priorities of every examination requested. This priority is used to determine what we call *appointment modifiability*. Appointments for outpatients are not modifiable, appointments that are part of an examination chain are barely modifiable and appointments for ward patients are easily modifiable. All this allows for relocating already scheduled appointments in favor of a high priority new appointment. In case of relocation, all affected entities are informed and rescheduling is initiated automatically.

To leave some degree of control on appointment scheduling in the hands of the people working in the diagnostic units, we have introduced a threshold for automatic booking of appointments. This threshold represents a certain relative time point in the near future (for example "in one week"). Though the system may automatically propose appointments lying within the time interval defined by this threshold, diagnostic unit users must give final permission for the appointment to become fixed. Appointments lying beyond the time point defined by the threshold are allowed to be automatically fixed. The semantics of this threshold is the representation of the desire for controlling one's own near future, while not really caring for appointments that lie far in the future. Another property in this context is that the future time intervals have to be actively released by the employees of the diagnostic units. This allows to flexibly determine uncommon off times.

Requesters like wards or the outpatients' department can control the scheduling process by providing information on desired time intervals for appointments, priorities and other restrictions like appointments in other clinics. People in the outpatients' department usually receive several alternative appointment possibilities for their requested examinations and can interactively select one or reconsider their desired time interval. People at the wards can select patients to become aspirants for fixed appointments or to be registered in the priority queue.

2.3 Modeling

Appointments in general In the following, we will describe a static variant of our medical scheduling problem. Components of the presented algebraic tuples are accessed by the "." operator. So, $x.name$ denotes the projection on the component with name *name* of the tuple x.

In medical appointment scheduling we are doing constraint satisfaction and optimization over finite domains. Hence, we have to enforce the existence of a scheduling horizon.

Definition 1 (Horizon). *A* horizon $h = \{0, \ldots, H\}$, $h : 2^{\mathrm{N}} = \mathcal{H}$ *is a finite set of integers that represents the set of possible starting points for appointments. Given a constant number of starting points per day nd the* day horizon *can be defined as* $h' = \{1, \ldots, H \text{ div } nd + 1\}$. □

The central term in our domain are appointments. These objects are used to encapsulate all domain variables, initial domain information and given constants of an appointment. The definition of an appointment bases on the definition of time slots.

Definition 2 (Time slot). *A* time slot t *is a pair*

$$t = (start, duration), \qquad t : (h \times \mathrm{N}) = \mathcal{T}.$$

start is a variable ranging over the horizon h representing the starting point of t. duration is a constant representing the fixed duration of t. □

Definition 3 (Appointment). *An* appointment a *is a 9-tuple*

$$\begin{aligned} a &= (id, type, slot, desstart, day, \\ &\quad pr, workpl, desworkpl, resource), \\ a &: (Id \times \mathcal{AT} \times \mathcal{T} \times h \times h' \times \\ &\quad \mathrm{N} \times \mathcal{W} \times \mathcal{W} \times \mathbb{N}) = \mathcal{A}. \end{aligned}$$

id is an identifier. type refers to an appointment type (see 2.3). slot refers to a time slot. desstart is a constant that denotes a desired starting time point of the appointment. day is a variable denoting the day of the appointment's starting time point. pr is the appointment priority. workpl is a variable that represents the choice of a concrete workplace for the appointment (see 2.3). desworkpl denotes a desired workplace for the appointment. resource represents the human resource demand of the appointment. □

Using the combination of *desstart* and *priority* we can implement the described strategy of appointment relocation and appointment modifiability. When requesting the scheduling of a set of new appointments the scheduling of recent appointments is also reconsidered. Though recent appointments may be relocated in favor of a high priority new appointment request, usually they should remain at their determined location. This is expressed using the *desstart* component. The *priority* component of such recent appointments has to be high enough to avoid superfluous relocation. This is a matter of defining the optimization criterion which is discussed in 3.4. $desstart = -1$ indicates an appointment that has to be scheduled as soon as possible. *day* is a transformed variable that ranges over h' and is bound to the appointment starting time point by defining the number of starting points per day *nd* and posting the FD constraint *a.slot.start* #= *nd* * (*a.day* - 1) + *Rest* (with $Rest \in \{0, \ldots, nd - 1\}$).

Provider objects In our application context, diagnostic units are providers. Every diagnostic unit provides a unique set of examination types. Hence, there is no choice between diagnostic units for doing a certain examination. Nevertheless, many units have several sub units, called workplaces. In contrast to the diagnostic units, the capabilities of these workplaces are not disjunct. So we have to introduce choice on the concrete workplace in a determined diagnostic unit. This choice is constrained by the appointment types provided by the workplaces. Appointment types are defined as follows.

Definition 4 (Appointment type). *An* appointment type *at is a 4-tuple*

$$at = (id, StartRange, MaxPerDay, ChangeTimes),$$

$$at : (Id \times 2^h \times 2^{2^{\mathcal{A}\times\mathcal{A}\times\cdots}} \times 2^{2^{\mathcal{A}\times\mathcal{A}}}) = \mathcal{AT}.$$

id is an identifier. StartRange is a subset of the horizon h and represents possible starting times for appointments of this type. MaxPerDay is a set of constraints with dynamic arity restricting the maximum number of appointments of this type for each day. ChangeTimes is a set of binary constraints enforcing constant buffer times between two appointments of this type. □

MaxPerDay is motivated by the fact that people in the diagnostic units want to control the maximum number of appointments of the same type each day. *MaxPerDay* can be easily implemented by using several ECL^{i}PS^e `atmost` constraints. *ChangeTimes* is technically motivated by necessary change times between two distinct examinations of the same type. Given the necessary change time c, *ChangeTimes* can be implemented by a set of $a_1.slot.start$ + $a_1.slot.duration$ + c `#<=` $a_2.slot.start$ `#\/` $a_2.slot.start$ + $a_2.slot.duration$ + c `#<=` $a_1.slot.start$ constraints.

Besides the different appointment types, every workplace can have individual off times which restrict possible starting times of appointments. Off times are usual time slots with a fixed *start* component.

Definition 5 (Workplace). *A* workplace *w is a triple*

$$w = (id, AppTypes, OffTimes),$$

$$w : (Id \times 2^{\mathcal{AT}} \times 2^{2^{\mathcal{A}\times\mathcal{A}\times\cdots}}) = \mathcal{W}.$$

id is an identifier. AppTypes denotes a set of appointment types provided by the workplace. OffTimes is a set of constraints with dynamic arity restricting the starting times of appointments to form a mutually exclusive schedule. □

The definition of a diagnostic unit is now canonical.

Definition 6 (Diagnostic unit). *A* diagnostic unit *u is a triple*

$$u = (id, Workplaces, Resources),$$

$$u : (Id, 2^{\mathcal{W}}, 2^{2^{\mathcal{A}\times\mathcal{A}\times\cdots}}) = \mathcal{U}.$$

id is an identifier. Workplaces is a set of workplaces belonging to this diagnostic unit. Resources is a set of constraints with dynamic arity restricting the maximum number of resources available for parallel appointments at the workplaces. □

Resources is motivated by the fact that though there may be several workplaces in a diagnostic unit not all of these may be usable in parallel. For example, staff is assigned to diagnostic units and not to workplaces. Hence, if an appointment requires two technical assistants and one doctor (denoted by the *resource* component of the appointment), no other appointment may be possible, though other workplaces may be free. *Resources* is implemented using ECL^{i}PS^e's `cumulative` constraint over all workplaces of the diagnostic unit.

Alternatives in choosing workplaces can be modeled in CHIP by using the `diffn` constraint, which is very efficient in handling process alternatives. ECL^{i}PS^e provides only the `cumulative` constraint, which can be interpreted as a one-dimensional specialization of `diffn`. Nevertheless, it is well known that `diffn` can be emulated with `cumulative` constraints by introducing choice variables and transforming the given starting time variables to new variables. A new variable is then bound to the sum of the standard starting time variable and the product of the choice variable and the horizon. For example in case of two workplaces in a diagnostic unit, the scheduling horizon doubles and the transformed variables have a domain twice as large as the standard starting time variables.

Requester objects Requesters can be interpreted as representatives of a set of patients. In appointment scheduling, a patient is mainly defined by his/her assigned partially ordered set of (open/fixed) appointments and a basic priority.

Definition 7 (Patient). *A* patient *p is a 5-tuple*

$$p = (id, Apps, Order, Excl, pr),$$

$$p : (Id \times 2^{A} \times 2^{2^{A \times A}} \times 2^{2^{A \times A \times \cdots}} \times \mathbb{N}) = \mathcal{P}.$$

id is an identifier. Apps is a set of appointments. Order is a set of binary constraints over appointments, defining a partial order on the patient's appointments. Excl is a set of constraints restricting parallel appointments for this patient. pr is a priority. □

Since patients can only undergo a single examination per time slot every appointment has to be executed mutually exclusive. *Excl* guarantees this by posting corresponding `cumulative` constraints over the sparse "resource" patient.

3 Distributed CLP solving

3.1 Motivation for distribution

The problem modeled by the variables and constraints mentioned above could be solved completely by a monolithic CLP solver. Though this possibility exists

in principle, it is usually not practicable in real medical application setting. The information on variables and constraints is spatially distributed among the many departments of the clinic. Even in case of a monolithic solver one would have to collect all the information from its several sources, transfer it to the solver, solve the problem and again distribute the results of optimization among the different users. Hence, even in case of a central optimizer one has to cope with communication and information consistency problems.

A second argument for distribution is the poor scalability of central solvers. As soon as not only one clinic of Charité Berlin would be connected to the appointment scheduling system, a solver would be needed that would have to compute the solutions for all connected clinics. As experience with CLP shows, problems get quickly too complex to be solved efficiently with such an approach. Since constraint satisfaction is known to be NP-hard, the only way to cope with this complexity problem is to partition the problem and accept inevitable suboptimal solutions. At this point, distribution is a should-have.

A third argument against a central solver is privacy. Social structures especially in hospitals have created a heterogeneous field of competencies and influences. No director of a single clinic would accept transferring all his or her clinic's appointment data to another clinic for global optimization. Even less she or he would accept automatic control over her/his clinic's appointments from a central instance. For acceptance, there have to be secure interfaces between realms of competency that only let pass authorized and restricted information. Decisions on appointments have to be done at the same locations of competency where examinations will take place in reality. At this point, distribution is already a must-have.

A last argument for distribution is redundancy and responsiveness. A crash of a central solver or missing connectivity would influence the whole hospital leading to chaos. Master/slave concepts raise the amount of communication overhead by caching and mirroring. In contrast to that, the crash of a single optimizer in one diagnostic unit would influence only that unit and its neighbors.

Despite these advantages of distribution, such systems have also major disadvantages. The complexity that has been saved within the several solvers is transfered to the coordination process. Due to this fact, investigations on todays distributed solver systems often report poor optimization results or vast communication overhead. The traditional approach to distributed problem solving is to design the distribution aspects off-line by statically assigning certain roles and competences to specific agents. Thus, the problem space is statically distributed among a more or less fixed set of agent types. Our approach differs from this by trying to allow on-line modification and reconfiguration of the MAS structure. Together with measures for internal problem solving complexity and communication overhead, the system shall automatically adapt to the current problem structure by melting and splitting problem solving knowledge, tasks and skills. A step towards this target are *composable agents*. This term denotes entities that are built of certain independent components, which represent pieces of knowledge, goals and problem solving capability. By exchanging

their components these entities can dynamically reconfigure to fit the current situation better. More detailed information on composable agents and dynamic reconfiguration can be found elsewhere [8, 9]. In this article we will focus on the coordination aspects for controlling the interaction of distributed CLP solvers.

Though the structure of distribution is not fixed in our approach to distributed CLP solving, one has to start the system with an initial distribution. Following natural distribution and competency areas we have defined agents that care for patients, agents for requesters in general and agents for diagnostic units. Figure 1 shows a distributed constraint graph with two patient agents and two diagnostic unit agents. As can be seen in the figure, not only variables (appointments a_1 to a_7) are denoted by nodes and designated to agents but also complex constraints (the *cap* node denotes all constraints mentioned above under the provider's view). Thin lines illustrate constraints within an agent. Thick lines illustrate constraints between agents. Dashed lines mean partial order time constraints, solid lines capacity constraints.

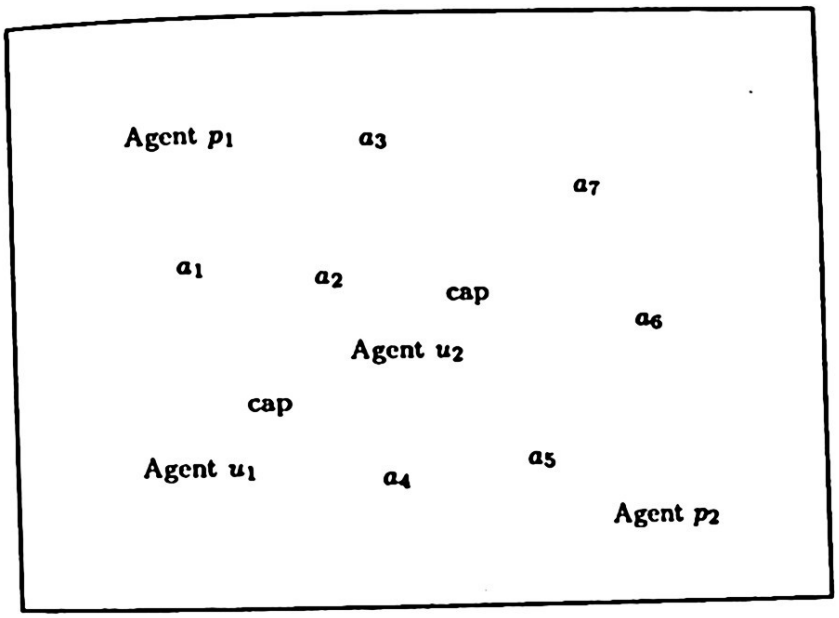

Fig. 1. Distributed Constraint Graph

3.2 Implementation tools

While (constraint) logic programming languages are well suited for knowledge-based computing, like reasoning, planning and optimization, they are not well suited for distributed computing. Therefore, we have decided to use a hybrid tool set of languages each of which fits best to the specific problem.

In Charité Berlin we are facing a pure Windows NT environment. Hence, we are using Microsoft's *Distributed Component Object Model* (DCOM, a CORBA like object request broker) and Message Queue Server (MSMQ, a fully transparent email service for programs) as communication foundations that provide

useful abstractions from usual communication protocols, like TCP/IP. Access to DCOM and MSMQ is best done via Visual C++ providing the speed we need. User interfaces can be rapidly developed using Visual Basic. For the internal realization of problem solving agents we use ECL^{i}PS^e since it is highly expressive, efficient and free of charge for research projects. Additionally, ECL^{i}PS^e functionality can be linked into C++ code via a Dynamic Link Library (DLL). To put it into a nutshell, the system is controlled by C++ code, displays data with VB code and solves complex problems with ECL^{i}PS^e code.

3.3 Mechanisms for coordination

Algorithm 1 solve(A)

{Compute all neighbors holding constraints on A.}
$N \leftarrow$ `comp_neighbors`(A);

{Collect declarative information on all constraints imposed on A from all neighbors and store it in the set of external constraints C_{ext}.}
$C_{ext} \leftarrow \emptyset$;
for all $n \in N$ **do**
  $C_{ext} \leftarrow C_{ext} \cup$ `requ_ext_constr`(n, A);
end for

{Compute internal constraints on A, compute the local optimization function z and find a solution s to A internally w. r. t. C_{ext} and C_{int}.}
$C_{int} \leftarrow$ `comp_int_constr`(A);
$z \leftarrow$ `comp_int_opt_crit`(A);
$s \leftarrow$ `solve_int`(A, C_{ext}, C_{int}, z);

{The information on external constraints is not static (committed) and asynchronous solutions of other agents might have invalidated C_{ext} and thus s. Hence, the agent must inform all neighbors on its new solution to A. Nevertheless, it assumes that the problem is solved and sets the state of A optimistically. To react to asynchronous information on A the agent calls a monitoring function for each $a \in A$.}
for all $n \in N$ **do**
  `inform`(n, A, s);
end for
for all $a \in A$ **do**
  a.`solved` $\leftarrow$ `true`;
  newThread (`monitor`(a));
end for

In the case of distributed problem solving, it should be the same whether the constraints between appointments are internal to a unique agent or externally distributed among several agents. The coordination protocol should allow for both. The following algorithms describe parts of a first approach to a flexible

coordination protocol for distributed CLP solvers. Algorithm 1 implements an external request for constraints on the current given set of appointments A that have to be scheduled. This algorithm describes the view of a requester.

The algorithm has three stages. In the first stage, the agent collects information on constraints restricting its set of appointments A. This stage could be called *external constraint propagation*. This is done by determining all neighbors of the agent that hold constraints on A and then requesting declarative descriptions on their constraints. The degree of declarative description is dependent on social restrictions mentioned above. A neighbor that belongs to another competency realm may only answer with a restricted domain on A. A neighbor from the same competency realm may provide more information (for example all constraints described above, which would correspond to providing information on the whole current schedule) to allow for a higher quality solution. The advantage of CLP in this case is the possibility to encode even complex constraints in relatively simple string expressions that can easily be exchanged among agents.

In the second *internal propagation and search* stage, the agent collects its own internal constraints on A, computes a local optimization criterion on A and finally uses its internal solving capability to find a labeling for A[1].

In the third *monitoring* stage, the agent informs all neighbors on its solution and starts monitoring on the single appointments in A. This is shown by algorithm 2. Monitoring primarily means watching the acceptance of other agents for the proposed solution. In case of a NO-GOOD message from one of the neighbors, the agent retracts its solution to a and restarts the solving process for a.

Obviously, this coordination protocol is not complete, because it may leave out certain solutions. Nevertheless, it is correct and can avoid cycles by defining a dynamic priority order over agents for keeping an agent from permanently retracting its solutions. And it is efficient since it does no backtracking, but rather a kind of backjumping. Apparently, this protocol works like a usual central CLP solver going through the stages of constraint propagation, labeling and monitoring, but all this in a distributed asynchronous manner.

3.4 Example for solving an internal problem

The previous subsection has assumed the existence of an internal problem solver that can obey external as well as internal constraints. If all external constraints are communicated in a CLP syntax they can easily be incorporated to a local CLP solving process. We will focus on the side of a provider to give an example for this. In the above described coordination scenario a requester would first of all request information on constraints on a set of open appointments A. The task of the provider is to answer the request for constraints lying on A according to its knowledge. The provider is assumed to be benevolent, so it will answer honestly. Nevertheless, it will follow its own optimization strategy in making

[1] Since there are usually no deadlines in medical appointment scheduling, we assume that there will be always a solution for A if the horizon is large enough. The difference is only the solution's quality.

Algorithm 2 `monitor`(a)

```
{Compute all neighbors of constraints on a. Wait for message or time events triggered
by a.}
N ← comp_neighbors(a);
e ← wait_for_events(a);

{React to the triggered event according to its type.}
select e
  {In case of another agent sending a "no-good" message
  retract s and inform all appropriate neighbors that a
  is unsolved again. Adjust state of a accordingly.}
  case NO-GOOD:
    for all n ∈ N do
      inform(n, a, ⊥);
    end for
    a.solved ← false;
    newThread (solve({a}));

  {Handle other messages according to a. }
  case ?:
    ⋮
end select
```

proposals for A. In our case, this optimization strategy tries to change as few recent appointments as possible, but to schedule the appointments in A as soon as possible in favor of the requester. Given the set of recent appointments A_R, the set of requested appointments A and a weight for penalizing displacement $displ$ this optimization strategy can be formalized by

$$z = \sum_{a \in A_R} [(a.slot.start - a.desstart) \cdot a.pr \cdot displ] + \sum_{a \in A} [(a.slot.start - a.desstart) \cdot a.pr] .$$

This value has to be minimized.

As usual in CLP, for reaching completeness not only the presented constraints have to be posted but all free variables have to be labeled by a heuristic search procedure. Starting time variables $a.slot.start$ and workplace choice variables $a.workpl$ are the free variables of our problem. Heuristics for choosing the next variable to label and for choosing the next value to assign to this variable are manifold and have been reported in several papers on CLP. In most cases, heuristics tailored to the application domain are most successful, since they can incorporate specific domain knowledge.

We have designed our labeling heuristics to fit the demands set by the optimization function presented above. Since we use a branch-and-bound method for optimization it is most important to find solutions with expected high optimality first to tighten the bounds on the searched solution early. That means to

label the variables starting with the highest optimality solution candidates even though risking inconsistency. Then we stepwise deviate from this solution until consistency is reached. In our example that means to start labeling variables with high priority first, because thereby they won't be subject to backtracking soon. In general all workplace choice variables are labeled first, because they often have much tighter domains than the starting point variables. For value ordering we use a special strategy that labels starting point variables initially from their desired value (*a.desvalue*) and in case of backtracking cyclically around this value (one value left, one value right, two values left, two values right ...). First simulations show that the combination of these variable and value ordering heuristics speed up the search for good solutions remarkably in comparison to standard labeling strategies.

The results of optimization on the provider's side can be reached back to the requester for constraining the choices on A. The requester will then calculate its own optimization function, for example minimizing the patient's stay in hospital or trying to create examination chains, and search for an externally and internally consistent good solution. This solution is handed back to the providers and they can decide whether the conditions under which they gave their proposals still hold. In this case, the reported appointments are fixed and go into the recent appointments. Otherwise, the providers can send `NO-GOOD` messages, thus restarting the process.

4 Comparison to other DCSP approaches

Most related work in Logic Programming and CLP has considered parallel evaluation of goals (and-/or-parallelism) or concurrent approaches using a shared store [17]. These approaches are interesting, but they are not fully applicable to the distributed setting found in medical appointment scheduling. More appropriate are approaches for solving problems known as *Distributed Constraint Satisfaction Problems* (DCSPs). Though there are DCSP models commonly excepted by several researchers, there are also some alternative models that allow for a different view on the problem and such for different algorithms.

An excellent, yet a little out-dated overview to DCSP models and algorithms is given in [15] and [12]. The authors identify four basic elements in solving DCSPs: centralized or decentralized control, shared or separated search space, message-passing or shared memory and termination detection. In this sense, our research tends to do coordinated problem solving with decentralized control, shared search space, message-passing and without termination detection. The latter is due to the fact that termination detection is not so important in dynamic problems, since new tasks may arise on any time. Luo et al. also present an interesting classification of DCSP solving approaches. They distinct variable-based approaches (in which every agent cares for a subset of variables), domain-based approaches (in which ever agent cares for a subset of values for a unique variable) and function-based approaches (in which costly computations in centralized CSP solving are distributed to speed them up). Our concepts are

designed to solve problems variable-based, since this is the only approach to allow for social and natural borders between subproblems. In [12, 14, 13] the authors propose different algorithms to solve DCSPs variable-based, domain-based and function-based. They all assume a binary DCSP and are hence based on simple constraint representations via no-good-sets.

An important contribution to DCSP solving has been given by Sycara, Roth, Sadeh and Fox in [20] in which they present *Distributed Constrained Heuristic Search*. They identify important characteristics of collaborative problem solving: global system goal to satisfy all constraints and minimize backtracking (equivalent to computational effort), concurrent and asynchronous variable instantiations, limited communication, incomplete information and potentially major ripple effects of backtracking. They also characterize the design trade-off for a proper level of distribution in a system for a given communication bandwidth, but do not address this problem in the paper. Though their proposal is mainly focussed on job-shop-scheduling they have already used a combination of distributed constraint propagation (in form of communicating resource demands) and distributed heuristic search (called *asynchronous backjumping*). The authors' introduction of special resource monitoring agents and job agents and the according cooperation protocol can be seen as predecessors of the ideas presented in this article. Sycara et al. characterize the effect of different decompositions and their characteristics to be a subject of future research.

Being another classical reference in DCSP, the work of Yokoo and Ishida introduces a DCSP model that simply assigns the variable nodes of a binary CSP graph to the different agents. Hence, this is a variable-based approach. Their main contribution lies in the development of distributed search algorithms, like *asynchronous backtracking* and *asynchronous weak-commitment search*. The earlier versions (collectively presented in [23] and [25]) relied on the assumption, that every agents cares for just one variable. Newer versions ([24]) overcome this restriction by allowing complex local problems. All these algorithms are correct and complete. To coordinate the different forms of asynchronous backtracking, the algorithms establish a static or a dynamic order among agents that determines the cooperations patterns between agents. In their work, Yokoo and Ishida mainly cover search and not so much constraint propagation. Additionally, the assumption of simple binary constraints restricts the applicability in real-world settings. Nevertheless, their coordination procedures have influenced much other work in this field. The same holds for the coordination protocols in this article.

Also in [25] two constraint propagation techniques are mentioned: a filtering algorithm reported in [22] and a hyper-resolution-based consistency algorithm described in [2]. The filtering algorithm achieves arc-consistency by communicating the domains of each process to the neighbors and removing values from these domains that cannot satisfy the given constraints. The hyper-resolution-based consistency algorithm applies a logical transformation rule to combine communicated constraints and information on an agent's domain to form tighter constraints. Both algorithms do not transmit abstract constraint information but concrete domains or no-good-sets of variable labelings that are inconsistent.

Hence, one weakness of these algorithms is the vast amount of communication since enumerating domains or constraints as simple data types can be highly space-demanding. The coordination protocol presented here uses high-level logic description to pass constraints from one agent to another, thus saving communication overhead. This is related to the work presented in [26]. Zhang and Mackworth propose a distributed arc-consistency check that uses an abstract constraint propagation facility and joins the communicated constraints with internal constraints. They also present complexity results for acyclic constraint graphs.

Another pre-processing distributed arc-consistency algorithm DisAC4 is discussed in [21] (see also [16]). It is a distributed version of the sequential AC4 algorithm and assumes that every agent is assigned exactly one variable. By simulating the behavior of several such agents more than one variable can be checked by a single agent.

Another approach to DCSP solving does not try to solve the DCSP with new distributed propagation or search methods but to facilitate existing CSP solvers to solve the problems local to an agent and then to combine the results of these solvers. An early reference on this approach is [1]. They introduce the notion of *interface problems* by partitioning a DCSP along variable nodes and not as usual along constraint arcs. All variable nodes that belong to more than one agent form a new problem — the interface problem. The variable nodes not belonging to the interface problem can be labeled independently from other variable nodes. Such, solving the interface problem and then solving the independent problems eventually using backtracking solves the whole problem. A disadvantage is the need for a global instance for finding the solution to the interface problem and collecting the solutions of the independent problems. Solotorevsky and others ([19]) follows a similar strategy by defining *canonical DCSPs* which consists of a special constraint graph connecting all independent local constraint graphs. Similar to Berlandier and Neveu they use common CSP solvers to solve the partitioned problems. All these authors assume a given partitioning of the DCSP and facilitate a global instance for guiding the solving process.

Solotorevsky and Gudes have applied their DSCP approach to time tabling in a hospital [18]. Decker and Li apply their generalized partial global planning approach to patient scheduling [3]. Despite these research efforts, we do not know any MAS that actually solves the problems we are facing in the ChariTime project.

5 Conclusion

Until now, the concepts presented here are just a vision. Nevertheless, our working groups have achieved promising results in central optimization by constraint-based approaches. Examples are job-shop-scheduling and time-tabling problems [4, 5].

The efforts in distributed CLP solving on the conceptual level and ChariTime on the applicational level are based on recent research in distributed production

control [6] and include besides the presented concepts business process modeling based on Petri Nets [7]. The ChariTime team is currently beginning realization and we hope to achieve first results at the end of 1999.

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Process Improvement with Simulation in the Health Sector

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Abstract. The need for organizations to became everyday more competitive, has made them to engage in the study and re-engineering of their processes trying to improve the form they perform their tasks. However, even though the number of organizations that are doing these kinds of studies is growing, the failing rate reported in the literature is high (Hlupic, 2001). One of the main reasons reported, is the lack of using tools that enable the analysis of the process from two different perspectives: static, by means of process modeling, that permit to obtain a general vision of the process and detect some fundamental problems; dynamic, using simulation techniques, to predict process behavior once this has been redesigned and before its implementation. With the use of the two techniques together, a more complete and accurate approach to the analysis and management of processes is expected. In this work we illustrate how process modeling and simulation can be used together during process analysis. We do this, with a real case study in the Mexican public health sector, in particular, in an emergency room service.

1. Introduction

Nowadays organizations require, every time more, to perform their tasks in a more efficient way. Therefore, they are more concerned with analyzing and improving their processes and engaging in re-engineering efforts. Although the number of organizations doing this is growing, the failure in these projects is over 50%. One of the main problems reported in the literature is the lack of using tools to predict process behavior once it has been redesigned and before implementation [Hlupic, 1998], besides the difficult task of capturing processes in a structured form. Health organizations are not an exception. In addition to the support that IT can provide in needs of clinical information, resources' management, etc. There exist a set of support tools that can be used to address the dynamic aspects of the medical processes such as computer simulation [Wainwright and Waring, 2000]. This provides elements to analyze and evaluate aspects related with times of the daily medical processes. Enabling with the last, the possibility to analyze resources, activities, space distribution, service and queue times, within others. However to

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successfully use simulation in process improvement, we need to integrate it with a study of the process structure to establish the flow of activities, roles and their responsibilities, information entities, etc. This can be accomplished integrating simulation with process modeling.

In this paper we present some results arising from the development of a case study developed in the public health sector applying process modeling and simulation, in particular, in an emergency room service. We used the steps of a standard process re-engineering methodology, which we will introduce in a later section.

The corresponding process model is very complete and complex. It contains many roles with different types of interactions between them. Some of the interactions produce dependencies between activities. Thus, if there are insufficient resources to carry out all these activities in a given time, some results could be bottlenecks due to lack of resources and bad coordination in timing.

2. Process Modeling and Simulation

Process models are used to capture, study and understand processes in organizations. The five basic uses given by Curtis et. al. [1992] are: (1) Facilitate human understanding and communication, by documenting and supporting procedures in organizations in a consistent and uniform manner. Creating a common ground of communication; (2) Support process improvement, by establishing the basis to define and analyze processes; (3) Support process management, giving the basis for comparing actual processes against those already established; (4) Automate process guidance, establishing an automated guide for the process by means of computerized tools; (5) Automate execution support, facilitating process enactment. Here a process is considered as a group of related tasks, which are performed by people and an IT system interacting together to achieve the goals of an organization. A good process model addresses the three important aspects in processes: Information Technology (IT) support of the process, social issues such as staff training, culture, etc, and the process itself [Warboys et al, 1999].

Static process modeling tools and techniques, such as Role Activity Diagrams (RAD)[Holt et. al. 1983, Ould 1995], Integrated DEFinition Method (IDEF0), etc., are used to capture processes both to help in their understanding and to highlight the important aspects of them, such as organizational goals, analysis of activities, protocols, etc. However, such techniques do not generally capture the dynamic aspects (e.g. time, process instances, etc.) of these processes and therefore cannot fully predict the results of any proposed changes that might be applied to them, whereas simulation models aim to do exactly this [Pegden 1997, Gladwin and Tumay 1994].

Process modeling is growing in importance as an application area for simulation, in particular in the evaluation of the design and redesign of processes (process improvement). Even though simulation alone could be used to capture a process and perform a redesign analysis, a more detailed analysis of different aspects

of an organizational process has to be carried out initially. Features such as what activities are being performed (functional view – activities well defined), when and how are being developed (behavioral view - rules of the process), where and whom in the organization are executing them (organizational view - responsibilities), and the entities produced and/or manipulated by the process, their structure and relations (informational view) [Curtis et al, 1992] have to be analyzed to provide a complete process analysis. Some information corresponding to the views is provided by a process model (activities, responsibilities, some entities, interactions between agents, etc.) and is not given by the simulation model. On the other hand, with the simulation model some details such as the behavior rules (times) and entities are very well defined. Therefore, the information provided by both models complements each other providing the details needed for a proper analysis of the process.

Process modeling can be used to analyze static aspects of the process such as: duplication of activities and documents, interactions between agents (communication and coordination problems), responsibilities no defined, analysis of the IT which gives support to the process, etc. On the other hand simulation can be used to address questions such as: What is the total process cycle time? How long do customers have to wait before being served? What is the best way to schedule personnel? Bottlenecks analysis (location and timing for processing them), etc., [Gladwin and Tumay, 1994].

Simulation techniques, on the other hand, enable a more dynamic approach to the study of organizational processes. It can be used to model a current, redesigned or not yet existing (for process design) process. In this manner the behavior of the process can be predicted and analyzed. Simulation of such complex systems is a way of promoting the understanding of current processes, and of any proposed changes to improve their performance. Because of its usefulness, simulation is usually considered as an integral part of the decision making process [Tumay, 1996], assisting in the prediction of the behavior of these processes by investigating "what if" questions. Thereby, facilitating the understanding of possible outcomes produced by change and verifying the implementation of the system with a simulation model.

To perform the case study in the health sector, we used the steps of the Process Analysis and Design Methodology (PADM) (Wastell et. al., 1994). PADM has 4 main steps: (1) Process definition, (2) Process capture (elicitation and modeling), Process evaluation (validation and analysis) and (4) Process redesign. The process definition and capture was obtained with interviews with the people (agents) involved in the activities. With this information the process modeling was performed using the Role Activity Diagrams (RAD) (Holt et. al 1983, Ould 1995). RAD is a structured technique that captures most of the main features of a process: roles, agents, objectives, activities, decisions, interactions, etc. (Miers, 1996). During the step of static analysis the process model helped in the understanding and highlighting important aspects of the emergency room processes, such as organizational goals, analysis of activities, protocols; and to detect some problems such as duplication of information, ill defined responsibilities, lack of Information Technology (IT), etc. While this technique does not capture the dynamic aspects (e.g. time, process instances, etc.) of the process and therefore cannot fully predict the results of any proposed changes that might be applied to them, simulation models aim to do exactly this (Pegden 1997, Gladwin and Tumay 1994). Thus, we took the process model

captured in RAD and mapped them to a Discrete Event Simulation (DES- entities, queues, servers, resources, etc.), to perform a dynamic analysis (Martinez and Mendez, 2002). The dynamic information that establishes the times that take to perform the different activities of the process were provided by the head of the emergency room, who supervises and monitors the process and the agents involved in its performance. During the process, these agents take the times concerning when they start and finish their activities for the medical attention. Every day, the head of the emergency room collects and concentrates the data to analyze the process behavior. The DES model was implemented with the ProcessModel simulation package. With this we could obtain a more dynamic view of the process and perform "what if" experimentation visualizing queues, waiting times, bottlenecks, resources needed to improve the process, statistics, etc. With the later, being able to predict the process behavior according to the data collected and the parameters of interest. The hope is that this might lead us to a position where a more complete and accurate approach to the analysis and management of processes is possible. In this work we present the development of the process study, from process modeling to simulation and discuss some issues that arise from their analysis.

A key feature of a process re-engineering is based on establishing which aspects of the process need to be improved. Therefore, it is necessary to know the aim of the process, its main inputs and outputs, the areas involved and in general the detail of how the process performs. During the step of capture we establish these aspects concentrating on the flow of information, the agents involved, and the activities that are being performed.

The emergency room process was captured by interviewing the process owners: medical assistants, nurses, physician, the head of the emergency room, social worker and patients that required medical attention. We also analyzed the documents and formats used for each agent involved in the process. These interviews and the analysis of the documents were the based for defining the process description and the simulation model.

2.1 Process Description

The process starts when a *patient* arrives to the emergency room and asks the *medical assistant* for medical attention, the *assistant* registers the *patient*'s arrival on the form for medical attention and visitors. There, the *patient* has to probe that s/he is registered for medical attention at the hospital. In the case when they do not have their documents with them, the *medical assistant* will have to verify their adscription on the computer system or request to the *social worker* to provide her with this information. In the cases when it has not been able to demonstrate the *patient*'s adscription s/he is provided with medical attention giving him or his family certain time to provide the corresponding documents. Otherwise he is translated to another hospital.

The *medical assistant* assesses the symptoms- according to his acquired experience - and asks the patient to wait or points him to get immediate medical

attention. At this time she fills in the medical note form with the general information of the *patient*. Once the *patient* is inside the medical attention room, he is stabilized if needed and get medicines and laboratory analysis if required. If the patient is very ill, then the physician assess if he requires to be hospitalized or even to have a surgical intervention. If the *patient* is hospitalized in the emergency room area another *physician* together with a *medicine student* check the medical note, the prescription and the diagnostic to verify the patient's health and continue with his medical care. When an emergency room *physician* arrives he starts his activities checking the hospitalized *patients* to decide if they go to a specialist or home. The *medical* assistant and the *physician* have to fill in several forms according to the activities that are performing. In these forms they record the service times to be analyzed later for the head of the emergency room.

If some medicine is required this is obtained with a medical prescription from an area called CENDIX. A nurse is in charge of the CENDIX and she controls the medicine and inventory. The *social worker* activities are to provide support to the *patients* and his family. She looks for the family of the *patient* in case that they arrived alone or need something, helps them with administrative forms, follow up urgent lab analysis, etc. *Nurses* provide support to the *physicians* in the *patient*'s medical care. They supply the medicine to the hospitalized *patients* and monitor the patient's health.

The *head of the emergency room* is in charge of supervising the activities of each of the agents involved in the process. In order to do that, every day he checks all the formats filled the day before and from them obtains statistics concerning the efficiency of the process.

Once obtained the process description we developed the static process models using the RAD diagrammatic technique.

2.2 Static Process Model Representation

The process models were captured with the RAD's graphical notation. RAD is a structured technique that captures most of the main features of a process (roles, agents, objectives, activities, decisions, interactions, etc.) [Miers, 1996]. In Figure 1 we present the basic elements of RADs highlighting the roles, which group activities performed by an agent to reach an aim. Roles are represented by a rectangle with a label at the top, specifying the role's name and the agent responsible to perform it. Inside the role the activities are drawn as small open squares with its description at the right, the interactions between roles are represented by bold lines, which connect from the role's activity that started the interaction to the activity of the role to which it is communicating. The vertical lines that connect the RAD elements are called state lines, which show the transition (states) between the elements. The decisions are small circles, where each one represents a particular condition or alternative path in the process. There exist also parallel or concurrent threads of activities, where the main characteristic is that they can be executed at the same time, and the activity that follows the set of paths can only be performed when all the threads of activities have finished. These are represented by small rectangles.

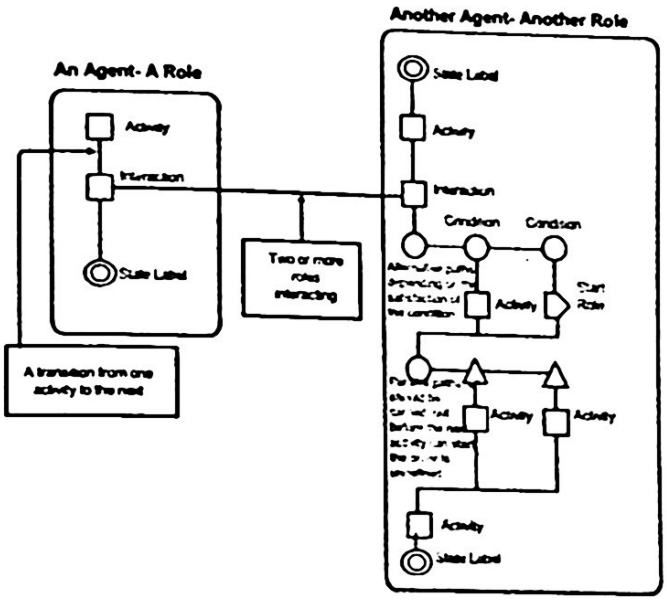

Figure 1. Graphical Notation for the RADs where it shows roles, activities, interactions, decisions, etc.

Figure 2 presents part of the process model of the medical attention at the emergency room. It illustrates the activities performed for the medical assistant and the patient at the time of first arrival, as described before in the process description. The process model was validated with the process owners. At the beginning some changes were done to finally obtain a process model that captures the real process.

3. Process Analysis

The step of process analysis is a key step in process re-engineering. Here we focused in finding points of improvement in order to propose a process redesign and support if necessary. We can perform two kinds of analysis: static, using process modeling, and dynamic with simulation models.

3.1 Static Analysis

During the static analysis of the process we have observed that the process satisfies its main objective. That is to provide medical attention to those patients that request it. However, we detected some problems in the process, where the technical aspects could be solved with the use of IT and the social with the creation of new roles and defining responsibilities in a more convenient way. With the use of IT we want to improve the performance of the process avoiding problems such as duplication of activities. On the other hand, the human aspect should be considered to

have a better work environment and facilitate the communication between agents of the process.

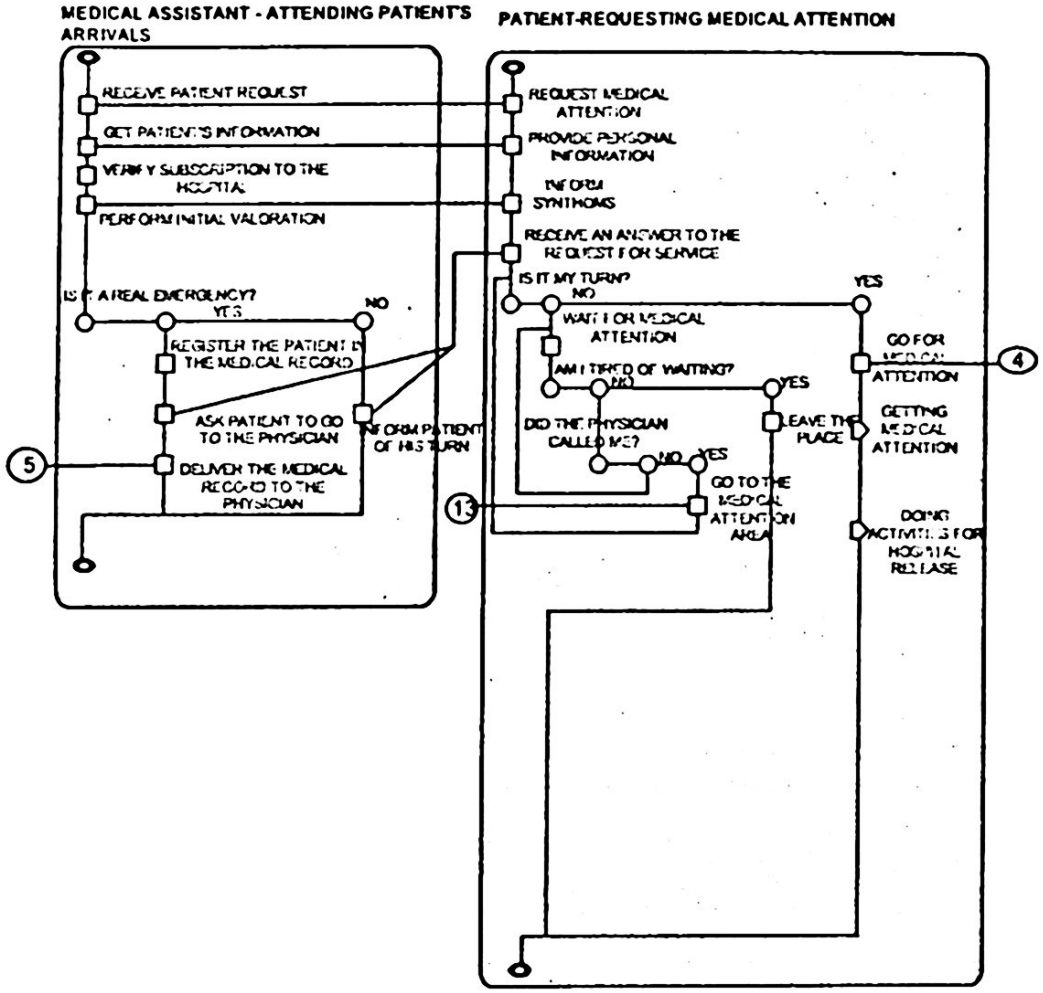

Figure 2. RAD diagram that shows: the activities that the medical assistant performs when a patient arrives, a patient requesting medical attention and the interaction with the system that verifies subscription to the hospital.

Some of the socio-technical points found during the static analysis of the process, based on the analysis of the process model are presented next.

- It is necessary to have a medical trained person, such as a physician, in the emergency reception area. A bad judge of a patients' case could be of deadly consequences. That is, there should be a new role in this area, eliminating the responsibility of classifying the emergencies from the medical assistant.
- There are some disagreements between some physicians about the use of new medicines. Some have the opinion that what the hospital offers is quite good and useful for many diseases, while others think that more and new medicine should be introduced.

- All the process information is captured manually in formats and the transcribed with a typing machine. This causes duplication of activities and may cause errors when transcribing the information.
- Sometimes there are many patients that have to be hospitalized and there are not enough hospital beds in the emergency area to do that. Neither enough space in the halls to put some extra beds.
- When there are not forms to capture certain information, this is written in a blank piece of paper that can be lost easily with other papers.
- There is only one computer in this area and is only used to verify the subscription to the hospital.

3.2 Dynamic Analysis

The dynamic analysis can be performed using simulation techniques that permit to determine the current and future behavior of the process. In this work we use Discrete Event Simulation (DES). The main elements necessary to build a DES model are illustrated in Figure 3. An entity is something (a person, a thing, etc) that is manipulated in the system (i.e. patients arriving at the emergency room, child or adult). The entities can have attributes (i.e. grade of illness). A queue is a collection of entities waiting for a service provided for a server (activities such as to evaluate a patient's health). A resource is a person or machine necessary to provide a service (a physician, a nurse) [Law and Kelton, 1991].

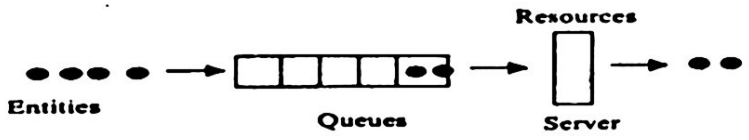

Figure 3. Basic elements of a Discrete Event Simulation model.

From the static process model in RADs we developed the DES models to perform a dynamic analysis of the process as it is. In particular we concentrated in the *subprocess of patient's emergency medical attention and reception.*

With the process models in RAD we obtained some information for the simulation model such as: the agents involved in the process, the activities performed, and the flow of entities. That is, the RAD provided the information to establish the DES model static structure. However RAD does not have information to determine the process behavior. Therefore we had to define the dynamic attributes of the process, such as inter-arrival times, service time, etc for each entity, to have a complete simulation model definition. This information was obtained from interviews with the head of the emergency room, where he provided us with a data concentrate of the timing of the process performance that they collect daily. From the model of figure 2 we defined the patients that required medical attention as entities of the process. Their inter-arrival time was established introducing the monitoring data of the process activities (of June, July and august) to the model. We represented the

activities carried out in the process as servers in the DES model and the agents that perform them as resources. Again we used times captured and processed from the real environment.

Analyzing the data provided for the head of the emergency room, we could observe that there was not timing information for all the process activities. Therefore, when building and simulating some of those activities in model we used times provided by the process owners according to their experience. The simulation model statistical data was not validated, thus the analysis of the model was more qualitative than quantitative, although we will show some numerical results from the experiments for reference.

Also from the data obtained we determined some parameters for the process flow and simulation such as: a probability of 56% for a patient to be hospitalized in the emergency room (observation area) and of 44% for those requiring other kinds of service among others. We established as well the number of human resources and their time schedule. There are three shifts: the first in the morning (7:00 to 14:00), the second in the afternoon (14:00 to 21:00) and the third at night (21:00 to 7:00). In the first and second shifts there is only 1 medical assistant, 4 physician (3 for the second) and 10 nurses. In the last shift is the same as the second but with 6 nurses. Other resources are the beds available at the hospital in the emergency room: there are 9 beds for adults, 8 in the children area and 10 in cubicles.

To determine the average times of the process, such as average inter-arrival, average service time per patient (in the different areas), with the data obtained from the clinic, we used the module *Stat::Fit* of *ProcessModel* [ProcessModel]. We obtained *a* ***Poisson(14.5)*** probability distribution for the inter-arrival, *Binomial(22,0.541)* for the service in the adults' observation area and *Poisson(11)* in the children's observation area (the observation areas are zones of hospitalization from hours to a couple of days). With the information gathered from the RADs and the head of the emergency room, we defined and implemented the dynamic simulation model of the *patient's emergency medical attention and reception subprocess* in the visual simulation tool ***ProcessModel.*** The model is presented in Figure 4.

In *ProcessModel* the simulation models are built using visual objects that represent the organizational elements such as entities, activities (servers), waiting lines, resources, etc. The simulation model of figure 4 was presented to the head of the emergency room to validate its structure; this is the flow of entities, activities and agents involved in the process. During this meeting the head of the emergency room requested some specific experiments during the dynamic analysis of the process such as: total of patients attended in a given time, how many were sent to the area of adults or children observation, and how many to the hospital or other areas.

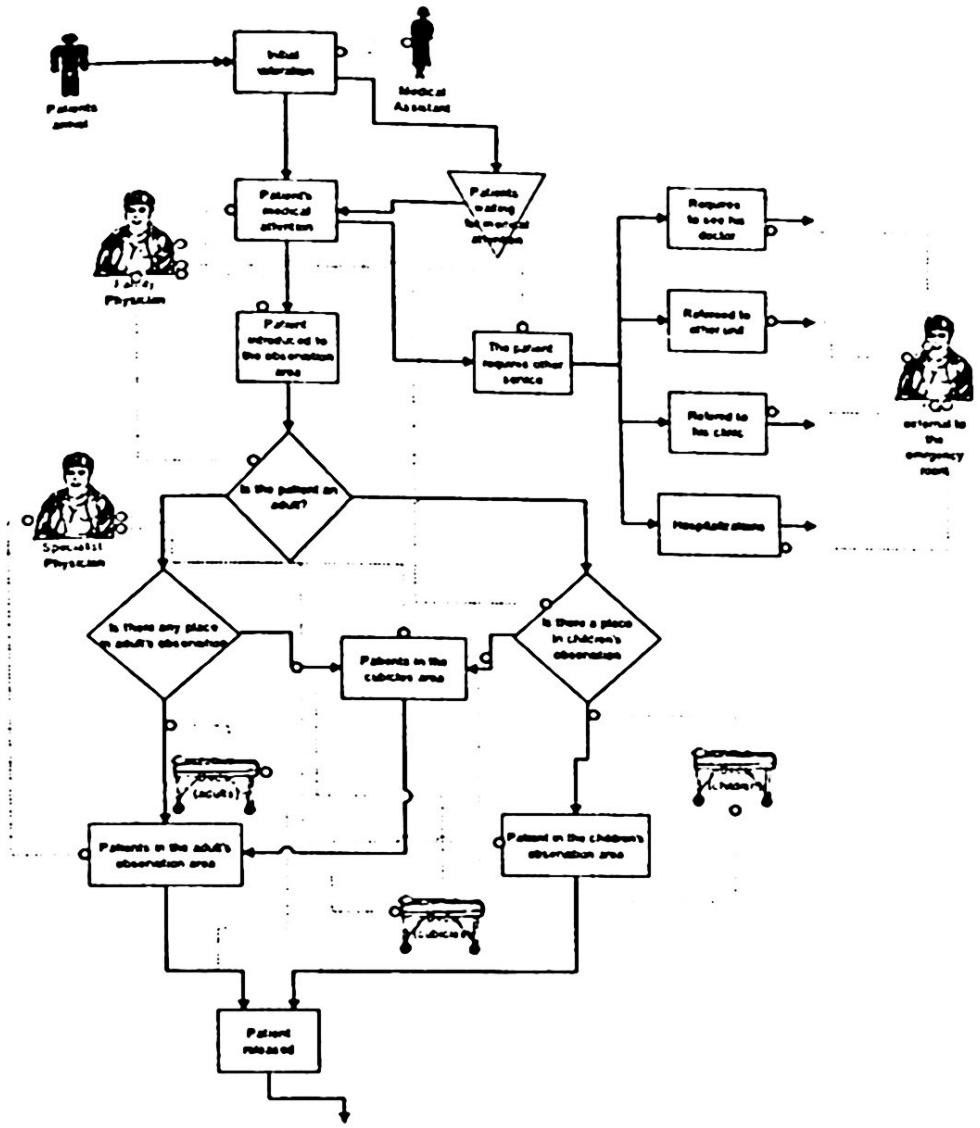

Figure 4. Simulation model of the *patient's emergency medical attention and reception subprocess.*

To perform the experiments we defined some variables in the model for both collecting the statistical data and introduce part of the flow of the process, for instance:

1. If there are not beds left at the observation area, the patient has to be located in the cubicles.
2. A variable to monitor the beds usage in each area, in such a way that if one is free, to transfer a patient from the cubicles to the observation area.
3. Also, it is necessary to monitor the availability of physicians that are providing consultations to the patients that do not need hospitalization.

One experiment carried out was to simulate the subprocess for a period of 744 hours, which corresponds to a month of service. This was performed to analyze and

predict the capacity of service of the emergency room. The process was simulated for a month (simulation time) as it is the format (per month) that the hospital uses to analyze and compare the services provided. Table I presents the results obtained from the simulation of the process.

Table I. Results obtained from the *patient's emergency medical attention and reception subprocess* simulation.

Statistics	Result per month
Patients provided with medical attention	2378
Patients in the adults observation area	817
Patients in the children's observation area	216
Patients requiring consultation with their physician	12
Outcoming patients referred to their clinics	1036
Patients referred to other hospitals	14
Patients sent to hospital	283

Table I shows that the capacity of service of the emergency room is of 2378 patients attended per month, according to the established conditions. From those, 817 are adults, while 216 are children. From the total 1345 need some sort of referral to other services. The results obtained from the simulation were compared with concentrated of data provided from the head of the emergency room and the simulation was very close to the data. The simulation of the model enabled us to analyze the rate of utilization of the resources. Figure 5 shows the result of the human resources and Figure 6 the utilization of beds.

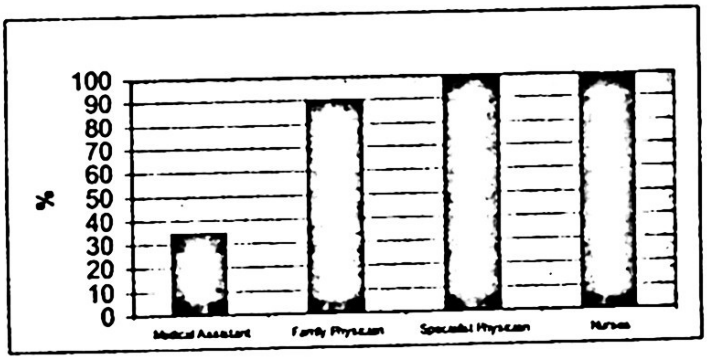

Figure 5. Utilization rate of the human resources of the process.

Figure 5 shows how the physicians, medicine students and nurses are always at their maximum level of utilization (90, 99.61 y 99.18), while the medical assistant only at a 34.5%; this is in the patient's evaluation not at the administrative tasks. If we add the last to the medical assistant his rate of utilization will go to the top. Other resources necessary to provide medical attention to patients in the emergency room are beds in the observation area. It is important to determine its rate of utilization.

Figure 6 shows this for cubicles, adults and children observation. The three go up of the 90%, showing that they are in constant use.

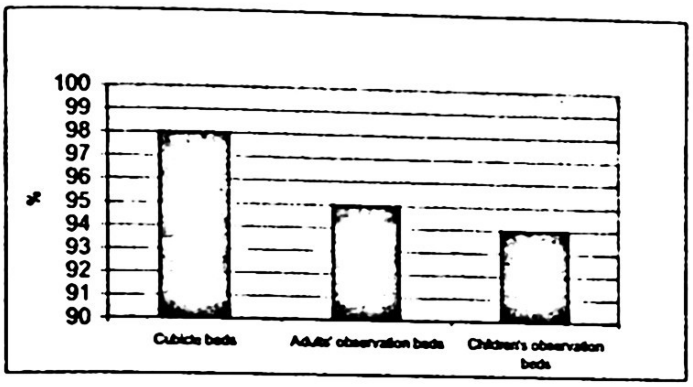

Figure 6. Utilization rate of the beds in the observation area.

Finally, the average time of permanence in the service of each area are: adult observation = 10 hours 43 minutes and children observation = 9 hours 44 minutes. The average number of patients waiting in the queue is of 740 patients per month. From the data, we could also observe many times the emergency room full and there with real emergencies still waiting to be attended. Therefore, the hospital tries to arrange sketchers and wheelchairs on the halls to provide medical attention to those who need it. This means that there is one more waiting line inside the area for medical attention; this is patients waiting for a bed. From the simulation we obtained that: 734 patients a month wait for medical service in this form.

From the analysis of the dynamic model we can determine the need of more human and material resources to increase the service capacity. On the other hand with the static model we found some socio-technical problems to be addressed in order to improve the form the process is perform. In order to improve the process performance a process redesign was proposed and evaluated.

4 Process Redesign

From the analysis performed we proposed a process improvement. Some aspects to improve were suggested by for the process owners while others emerged from the static and dynamic analysis done previously.

The static analysis enabled us to detect the need to create a new role in the reception area. It is the medical assistant who classifies the emergencies without much medical training. A proposal for improvement provided by the head of the emergency room when discussing the process model was to implement an area with a physician and a nurse (TRIAX) to perform the first medical evaluation of the patient. Here, it will be the physician who will define the kind of emergency. Other possibility for improvement will be to increase (double) the size of the area of the emergency room

to allocate more observation beds. This was detected with the dynamic model. In the TO-BE (redesign) simulation model we perform some experiments with 10 more beds that in the current model (this is 20), 5 for adults' observation and other 5 for children's observation. Also, as we observed the rate of human resources utilization is higher than the 90%, therefore we increase the personnel by 2 more physicians and 1 more nurse for each observation area. This is 4 more physicians and 2 more nurses.

Table II. Results obtained from the redesigned process simulation model.

Statistic	Result per month
Patients provided with medical attention	2794
Patients in the adults observation area	1150
Patients in the children's observation area	349
Patients requiring consultation with their physician	15
Outcoming patients referred to their clinics	1041
Patients referred to other hospitals	17
Patients sent to hospital	278

The redesigned dynamic model was simulated for the same period of time of the original process model (744 hours). The results obtained are illustrated in table II.

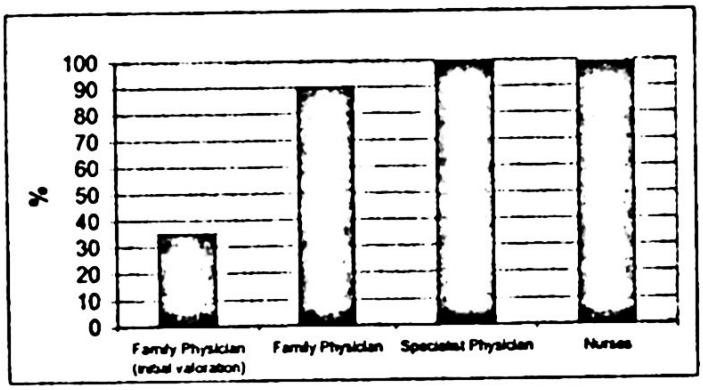

Figure 6. Rate of utilization of the human resources after process redesign.

Table II shows the effects of the redesign process: the emergency room provides service to more patients, 2794 consultations per month, 1150 attended in the adult's observation area and 216 to the children's observation. Of the 2794 patients, 2408 required to be referred.

Concerning the resources rates of utilization, the redesigned process simulation gave us very similar results (Figure 6 and 7). That is because the demand for medical service is still very high.

In the simulation of the AS-IS process we did some experiments, and we could observe bottlenecks generated in the waiting (for medical attention) and observation area (waiting for a bed). However, in the experiment of the TO BE process, we doubled the number of beds for observation and increased the number of human

resources in the observation areas and with these changes the queue lengths in the waiting and observation area decreased. This behavior is because more patients were provided with medical attention. In the observation area (including halls) the queue completely disappeared with the increment in the number of beds.

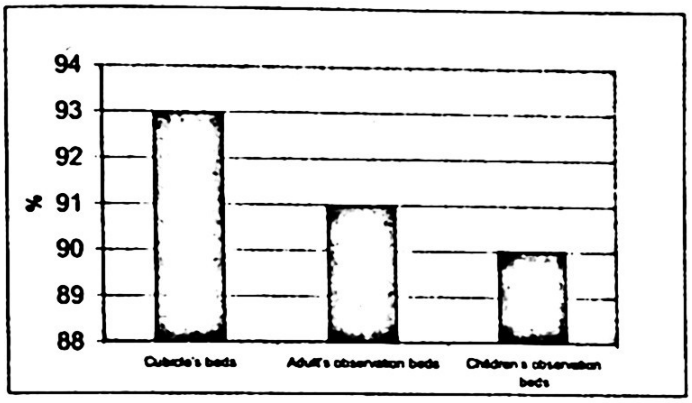

Figure 7. Rate of utilization of beds in the observation area for the redesigned process.

With all the proposed changes the number of patients provided with medical attention will increase around a 20%. Many more experiments can still be performed to verify the improvement in the process redesign or evaluate other alternatives.

5 Conclusions

In today's competitive environment the need for process analysis and improvement is everyday more evident. Therefore, process innovation or re-engineering projects will continue. To make more accurate decisions concerning changes in the way process are being executed, it is necessary to contemplate different alternatives that can be evaluated by the analysis of the process with simulation studies.

The process study presented, permitted us to evaluate under a real case scenario, the benefits that can be obtained from the use of both, static and dynamic analysis. The static analysis enabled us to understand and get a general vision of the process, as well as to obtain information about the socio-technical problems and provide some support in that area. On the other hand, the dynamic analysis enabled us to get a dynamic vision of the process behavior and its current state, observed problems such as bottlenecks, availability and utilization of resources, and to predict the results of changes in the process behavior by performing "what if" experiments.

The results obtained from the process analysis were presented to the head of the emergency room. He considered the process analysis results very useful for future changes in the process. The process model provides him with a feedback of the process and will be useful to communicate the process activities to new staff. On the other hand, the simulation model will provide him support to predict the process behavior and to validate possible changes in the process.

We can conclude that, a tool of this type with the integration of process modeling and simulation would be very useful in the health sector, particularly to predict patients behavior and be able to configure the resources for medical attention in the different processes of the hospitals and clinics.. The combination of both approaches provides a more detailed analysis of a process. On one hand the static process model facilitates the detection of fundamental problems (unnecessary or duplicated activities, no defined responsibilities, etc.). On the other hand, simulation permits us to evaluate the current process behavior and predict the impact of change.

Currently, we are developing a tool that integrates process modeling and simulation in the same software platform, where the simulation model is generated directly from process models captured in RADs. Furthermore we are working in the transfer of the knowledge of these kinds of means for process improvement with the medical sector and in the development of process support according to the information gather from real case studies and following a socio-technical perspective.

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Agent Based Scheduling of Operation Theaters

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Abstract. [4]
Medical operation planning is a substantial element of hospital management. It is characterized by high complexity, which is caused by the uncertainty between the offered capacity and the true demand. As emergency cases occur the planning requirements will change. Therefore, the use of a dialog-based system is preferred against full manual or automated systems, because of the inability of the latter to recognize the changes in a heigh dynamic environment. To make it possible to add new tasks in the planning process "on the fly" and to adequate the planning to new situations we involve a human planner in the scheduling process. The planner acts as a "sensor" for occurring changes and integrates his knowledge in the planning process.
In order for a created schedule to be accepted by involved personnel resources, it should include the interests and preferences of all the human actors. Existing planning systems do not take this into account and suffer therefore of in-acceptance of their resulting schedules. This leads to manual planning in hospital environments and binds a very specialized person to this task. It is required that the person should know the set of available resources, both material and human, requirements to medical operations and interdependencies among them. Nowadays, the medical director realizes this task. He is one of the most expensive resources in the area and his specialty is not the planning, but the surgery.
The presented work overcomes the drawbacks of existing solutions and includes the interests and preferences of each actor representing him/her through an intelligent, preference based agent. It also provides the mechanisms to solve the conflicts among them through a negotiation among agents.

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1 Introduction

Scheduling in hospitals is done in two phases, in the large and the small. On the long run, patients get an approximate date of operation, which in some cases - if it is not vitally necessary - might be several months ahead. In Germany, as in other European countries, the refunding system of hospitals by public health insurances is highly regulated and limited on a yearly basis, yielding to a backlog of wished operations. This backlog of several months essentially is caused by the limiting effects of available yearly budget, which yields to a steady number of operations per week independent of actual need.

A few days before the fixed date for the operation, patients enter the hospital to be prepared. Public health insurances are very eager to shorten the time of patient stay at hospitals before operation and will not refund any overtime. Thus, after admission of a patient, there is a definite need to do the planned surgery operation as soon as possible.

In the short run, scheduling of patients will happen from one day to the next. In the following, we will concentrate on this short run scheduling of operation theaters. Short term scheduling is well known being a process with an outcome that is highly dependent on situational variables:

- The duration of an operation in some cases cannot be determined beforehand. Thus, there is uncertainty of needed time.
- Also the specific tasks to be performed during an operation may depend on situations not observable during diagnosis (planning phase).
- The daily schedule often will be interrupted by incoming emergency cases. The frequency of emergencies depends on the medical department. For example, schedules of orthopedic departments seem to be very stable, whereas schedules of surgical of neurosurgical departments in general have to take incoming emergencies into account.

If a patient is scheduled for operation today, it may happen that by incoming emergencies, he suddenly will find himself in a position to be rescheduled for tomorrow. In the analyzed hospital this rescheduling results from a contract between nurses and hospital management that limits regular operating time from 8.00 o'clock in the morning to 4.00 o'clock in the afternoon at the latest. Management had been forced to sign this contract, since dissatisfaction of nurses because of working overtime on a regular basis had been overwhelming. On the other hand, any rescheduling of an operation of one day to the next is a major source of dissatisfaction of patients, physicians, and management. It essentially contributes to the increase of the backlog and causes possible shortcuts of refunding, since public insurances will not pay overtime in front of surgery operations.

2 Description of the Approach

The scheduling problem presented here leads to different requirements for a multi-agent system. First, human interaction should be reduced to a minimum,

thus reducing the needed time to resolve incompatibilities by phone. Second, the planning procedure should be done simultaneously, thus allowing for more flexible solutions, which for example utilize the available operating rooms more intensively. Third, a multi-agent system should take care of the individual interests of the involved personnel whenever possible. This will give strong evidence for the acceptance of the planning system and will allow a better degree of satisfaction of staff.

As representative for each individual we use software agents that contain the preferences of their principal. The scheduling of actions and resources is made in two stages:

- In the first stage the scheduler creates a preliminary plan without respect to preferences. Therefore we can use known scheduling approaches and algorithms. The scheduler interacts with the planner via dialogs and offers him subplans for modification, reordering, or to place them into a Gantt-chart. Subplans consist of a set of actions, selected with respect to the constraints of the concepts of the used ontology OntHoS[5] [4] from the resource database.
- In the second stage the scheduler improves the preliminary plan with respect to the preferences of each individual. When a conflict between the specified preferences of two or more individuals is found, the representative agents of these individuals should negotiate together with the goal to obtain a commitment. This means that only one agent obtains the conflicting resource that is specified in the preferences of all these agents while the others obtain adequate wages from the winning agent.

For the implementation of this approach some mathematical assumptions and restrictions regarding the preference ordering and importance have to be made. One restriction is that we suppose a linear ordering of all preferences specified by one individual. The used approach will work as well for partial orderings but it will become more sophisticated because of the additional transformation steps from one ordering to the other one. An other assumption that we make is, that the attributes of a preference can be randomly chosen from the set of all possible attributes.

Usually a negotiation supposes at least two parties, which have conflicting goals. These goals will be negotiated among the different agents by trading a bargaining-mass. Under the assumption that also different status levels in hospital hierarchy have to be taken into consideration this bargaining-mass will be weighted according to this status levels, e.g. a doctor gets more bargaining-mass than an operating room nurse.

2.1 Preferences

To describe motives and behaviors of persons there should be made a distinction between preferences and desires. Desires form a simpler and more basic notion than preferences. A desire for something involves only one object and refers

[5] OntHoS - An Ontology for Hospital Scenarios.

to a pro-attitude toward this object, whereas a preference for one object over one or more other objects involves at least two objects and indicates that the decision making person assigns a higher priority to his pro-attitude toward the first object than towards the others. Preferences therefore not only indicate the priority a person assigns towards his various desires, but indicate also the relative importance, which the decision maker assigns to his objects of desire. Because of this, the utility functions needed for the decision making component of the software agents can only be defined in terms of preferences, rather than desires. The set of all preferences $P := O^m$, $m \in N$ over the set of all preferred objects $O := \{o_1, \cdots, o_n\}$, $n \in N$ makes together with the relation $\prec \subseteq P \times P$, which represents the order of principal's preferences, its preference structure. The relation P is *irreflexive* (for no $a \in P$ is $a \prec a$ valid), *transitive* (if from $a \prec b$ and $b \prec c$, follows also $a \prec c$) and *comparative* (for all $a, b \in P$ is $a \prec b$ or $a \equiv b$ or $b \prec a$).

2.2 The Weight Function

The bargaining-mass is distributed over the specified preferences with respect to their importance. We assume that the importance of the preference at range i is higher than or equal to the sum of importances of all preferences with a range lower than i in the specified ordering.

The distribution of a bargaining-mass M over an ordering of preferences is made in the following way: the most important preference has the highest order in the specified ordering (i.e. if we have to deal with k preferences the highest order is k and the lowest is 1). This means that the preference with the highest order should obtain the highest weight of bargaining-mass.

This assumption leads us to the following requirements for the distribution function W of the available bargaining-mass (assuming p_1 is the least important preference) :

- The weight $w_i = W(p_i)$ of the preference p_i in the given order must be equal to the sum of the weights of the preferences p_j $(3 < j < i)$, which are less important than p_i.
- The weight w_i of the preference p_i should be greater than the weight of the single preferences p_j for all $i > j$ and $1 \leq i, j \leq k$. That means that the weight of the first two preferences, w_1 and w_2, has to be specified: $w_1 = m$, $w_2 = qm$. The range of values of m and q to simplify matters is restricted: $m \geq 1$ and $q \geq 1$.

The weight w_i of the other preferences can be calculated [2] as expected with a negative exponential function :

$$w_i = \frac{M}{2^{(k+1)-i}}, \text{for } 3 \leq i \leq k. \tag{1}$$

Due to the range values restriction of m and q is it possible to define only a limited number of preferences with a positive weight. The maximum number is

$k_{max} = \lfloor 1 + \log_2 M \rfloor$. In case of a greater number of preferences k than k_{max} of an actor, only the k_{max} most important preferences p_i (with $k - k_{max} \leq i \leq k$) are defined with a weight $w_i > 0$ and the other preferences p_i with the weight $w_i = 0$.

2.3 The Utility Function

During the negotiation an agent must be capable to distinguish whether the proposed changes will improve or impair the current state. The utility function $N(t)$ is the sum of weights of all preferences w_i at the time instance t:

$$N(t) = \sum_{i=1}^{k} w_i. \tag{2}$$

An agent will improve its state in a negotiation if $N(t) < N(t+1)$ will be true.

2.4 Preference Conflict Detection

In a common context the preferences specified by the actors can contain conflicts, because of the different and possible opposite goals that they should represent. Preference conflicts have to be solved and therefore, at first all the preferences involved in a conflict have to be detected. For this problem there exist many solutions based on graph-theory or resolution. The used approach is based on graph theory and works as follows: all the preferences $p_{j,i}$ (preference i of actor j) are inserted in a graph G as vertices and their ordering dependencies as directed edges $< p_{j,i}, p_{j,i+1} >$. If the insertion of a new edge forms a cycle with the existing edges of the graph, then the preferences represented by vertices on this cycle contain a conflict.

2.5 Preference Conflict Solving

The representative agents of the actors with conflicting preferences negotiate together with the goal to achieve an agreement. Therefore, the agents are initialized with the preferences and the weight volume of their actors. The weight volume is then distributed by the agents among their preferences. Afterwards, the scheduler asks each of the agents involved in the conflict for the weight of the conflicting preference. It selects the agent with the highest weight as the winner for the conflicting preference. The winner distributes then the weight of his preference to the other concerned agents with the help of a selected strategy, as those abandon one preference. The negotiation process ends with the returning of new weight volumes to the scheduler.

3 Implementation of the Approach

The described approach is implemented as a prototype in the framework for multi agent systems *Agent.Hospital* [5, 7]. The analyzed application scenario was

modeled with Protégé[6] with the help of the domain ontology OntHoS (see Figure 1, step 1). The ontology (T-Box) together with its instances (A-Box) were exported into the expert system JESS[7] as facts and rules (step 2). Further the A-Box, T-Box and all the problem solving methods as scheduling heuristics, conflict detection, negotiation strategies are implemented in JESS (step 3), and exported into the used JessAgents[8] (step 4). Further, all the agents are started and the schedulling process initiated by the PAScheduler agent. The user interface for interaction with the planner as well as the subplans generated based on ontological constraints are provided by this agent.

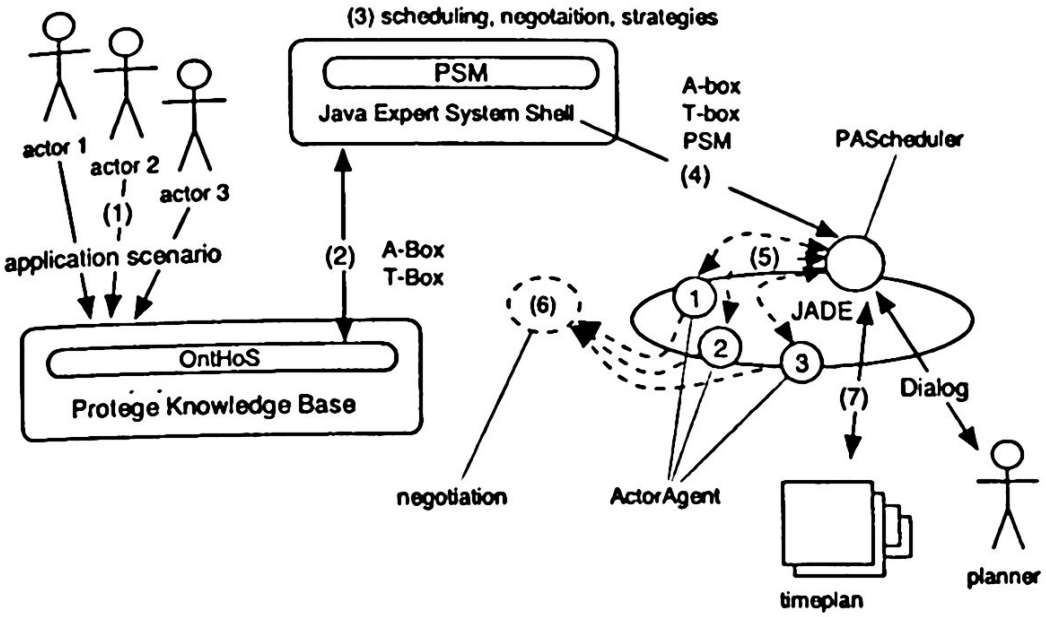

Fig. 1. Development Process Workflow

The agents are all initialized with the preferences of their principals and the weight volume with the FIPA[9] Request Interaction Protocol [9] (step 5). All the conflict solving negotiations are made with the FIPA English Auction Interaction Protocol [10] (step 6). Each solved conflict improves the preliminary plan (step 7) generated by the PAScheduler agent in interaction with the planner. This prototype was implemented with the help of the FIPA-compliant agent system JADE[10] [3]. The deployed agents are JessAgents (see Figure 2), developed to support a faster development process in agent technology. Problem solving methods and the behavior of a JessAgent can be written at a higher level

[6] Protégé Home Page. http://protege.stanford.edu/ .
[7] Java Expert System Shell. http://herzberg.ca.sandia.gov/jess/ .
[8] JessAgent Home Page. http://www-i4.informatik.rwth-aachen.de/agentcities/ .
[9] Foundation for Intelligent Physical Agents, http://www.fipa.org/ .
[10] Java Agent Development Environment, http://jade.cselt.it/ .

than Java programming without compilation of source code. Task ontolgies and problem solving methods can be loaded at runtime as well as a new fact base.

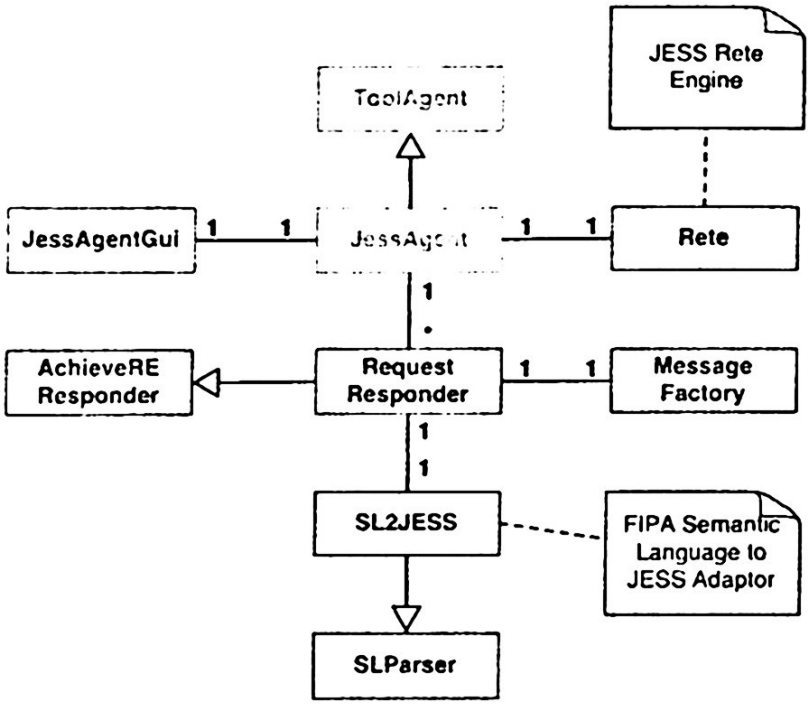

Fig. 2. Diagram of the JessAgent

Inside of a JessAgent all the received messages are translated by the SL2JESS adaptor to JESS functions, evaluated in JESS and the answer is automatically generated by the MessageFactory object with respect to the used interaction protocol, speechact, content language and the agent's fact base. All the rules, facts, and functions of an agent can be accessed by the developer through the agents GUI.

4 Outline and Conclusion

The presented work is work in progress. The selected scheduling heuristics as well as the implementation of the prototype give the possibility to test the presented approach in the lab. It remains to analyze the distribution of the weight volume among the agents during the continuous period of time, and to investigate different negotiation strategies. That is why the planning interface should be expanded in order to monitor planning actions taken by the scheduler. Time synchronization problems within the Agent.Hospital Framework should be solved with the help of an additional synchronization service [8] for agents. Further, the deployment of an ontology and a problem solving method repository [6] is planned and the test of the prototype inside of the agent.

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A topological map for scheduled navigation in a hospital environment

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Abstract. We present a new scheduler for navigation in structured environments. To achieve efficient navigation planning, a model of the environment supporting fast processing is required. We hierachically extract a topological map from a plot by using a new 3D data structure where nodes correspond to significant places in the environment. Paths linking this nodes are also hierarchically calculated. A TSP algorithm uses this topological map to efficiently schedule navigation tasks.

1 Introduction

Hospital Management is a hard task due to the complexity of the organization, the costly infrastructure, the specialized services offered to different patients and the need for prompt reaction to emergencies. Artificial Intelligence planning and scheduling methods can offer substantial support to the management of the hospital, and help raising the standards of service. Management, as pointed out in [4], is particularly important in a Rehabilitation hospital for a person with disabilities who - due to different pathologies - is no longer able to independently provide to his own self-care, and who needs the support of a second person to perform even the simplest every-day activities, referred to as basic Activities of Daily Living (ADLs).

To develop their work, the hospital member staff has to practice its daily assistance activity operating in wide spaces, thought to let proper movements to patients moving on wheel chairs, never forgetting their different planned schedule. In fact, during the whole day, the patients run through different peculiar activities, such as attending to the gymnasium for motory rehabilitation or into other laboratories for different recovery activities (logopedics, cognitive therapy, phoniatrics). Each floor has its own gymnasium and laboratories for his own rehabilitation goals. Preparing scheduling for physicians and nurses in the Rehabilitation department is a complex task, which requires taking into account a large number of rules, related to various aspects: the number of patients, the actual location of the patient related to the bedroom, the gymnasium, the priority of a patient compared to another, etc.

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A typical problem in such an environment where a staff member must accomplish several tasks at different places is in which order those places must be visited to work in an efficient way. Naturally, time and experience provide a valuable knowledge to the staff to organize their activity but unexpected emergencies or priorization make it difficult to follow the same pattern on a regular basis. In these cases, it would be useful to have a scheduling mechanism capable of providing the best plan to achieve the most optimal path through all required places as fast as possible. Also, the introduction of new mobile technologies like autonomous wheelchairs makes it necessary to develop such a mechanism to avoid constant reprogramming.

In its simplest formulation, the aforementioned scheduling problem can be briefed as, given a set of places to visit and the spatial relationship among them, finding in which order they must be visited to achieve the maximum possible efficiency. This is obviously equivalent to the well known Travelling Salesperson Problem (TSP). It must be noted, though, that the TSP does not provide information about how the agent, human or not, may reach each place from the previous one. The intention of reaching a goal point from a departure location while avoiding obstacles in the way is known as path planning. Path planning is required if the agent is mechanical so that it can be fed with the chain of movements required to navigate in the environment. Even if the agent is a human, it is also recommendable to solve navigation in case s/he is not completely familiar with the environment, it is in a hurry or an unexpected change, like a closed door, happens.

In this paper, a fast scheduling method for an efficient navigation in a dynamic structured environment is going to be presented. Whenever an environment is known, it is useful to use a model of such an environment for efficient problem solving. However, it must be noted that the TSP is a well known NP-complete problem and path planning is also very dependant on the size of the problem instance. Hence, an automatic map building method to extract a compact model of the environment from any available representation like a plot is presented in section 2. Using this representation, a TSP based scheduling method plus a path planning technique are presented in section 3. A real test environment is described in section 4. Experiments and results are presented in section 5. Finally, section 6 presents conclusions and future work.

2 A spatial representation for navigation

Spatial representations have been traditionally used for efficient navigation. Such representations must present free and occupied space as well as the relationship between the represented places so that paths can be inferred. The most classic representation is, obviously, the printed map. However, these representations have evolutionated to allow its processing by computers. Traditional spatial representations include metric and topological approaches.

Metric models of the environment rely on explicitly reproducing the geometry of the environment by using, for example, segment models [5], vertex models

[8], convex poligon models [3] or grids [12]. The main advantage of these representations is that they implicitly provide information about the relations among different places. Also, they can be extracted in a mildly fast way from a conventional printed map and some of them can also be easily generated by a mobile platform equipped with range sensors. Their main drawback is that their data volume may depend strongly on the complexity of the environment and, hence, the processing time of algorithms relying on them can not be predicted. Also, if maps are generated by a mobile platform, mechanical and sensor errors make it difficult to preserve accuracy in medium and large scale space.

Alternatively, topological approaches represent the environment by means of graphs, where each node is a place and the weights of the links joining two nodes are related to factors like the distance between them or the difficulty to travel from one to the other. There are many methods to create topological maps. Early algorithms relied on processing digitalized printed maps. Objects, modelled by polyhedra, were used to split space into a limited number of regions corresponding to rooms, doors or any other significant element. More recent approaches focused on building such maps by inserting a node each time a distant is travelled or each time a significant geometric beacon (e.g. corridor intersections) is detected in the environment. This process can be performed either a priori by a human observer or by a more or less complex automatic algorithm. Topological maps are reported to be more directly suited to problem solving [11] and more resistant to errors in mapping information. However, they are difficult to build when no layout information is known a priori and the information they provide about the relationship among nodes is usually vague. Some approaches combine metrical and topological representations. Zelinski [21] relies on partitioning a metric grid by means of quadtrees, but the resulting topological representation strongly depend on the environment layout and it is typically very suboptimal. Arleo *et al.* [1] model obstacle boundaries by means of straight lines, but they can not deal with irregular obstacles or wall which are not parallel or orthogonal. Thrun *et al* [17] split a metrical grid into regions by means of Voronoi diagrams, but it has been reported [9] that these maps, as well as other self organizing ones like the colored Kohonen map or the growing neural gas provide unintuitive tesellations. Kraetzschmart *et al* [9] extract walls from a grid by using wall histograms, but they acknowledge that their method does not provide suitable topologies to navigate in free space.

2.1 Data structure generation

We propose a new method to extract a topological map from a digital print of a map. The proposed technique is based on the split and merge paradigm but rather than an uniform grid or a quadtree a hierarchical data structure is used to support the node extraction process. Our previous approaches [18] to this process relied on the adaptive relinking paradigm [2], but in those cases it was not granted that resulting nodes were related to connected regions. To overcome this drawback, a new structure known as uncomplete pyramid is proposed. Given a digital 2D map of the environment where free and occupied nodes are printed

in different colors, say white and black respectively, this map becomes level 0 of the proposed structure, which is generated as follows:

1. Hierarchical structure generation. The map becomes the base of a pyramidal structure. Each level l of this pyramid is a reduced map with 1/4 of the cells of the level immediately below. Each pyramid cell (x,y,l) has five associated parameters:
   - Homogeneity, $H(x,y,l)$. $H(x,y,l)$ is set to 1 if the four cells immediately underneath have the same occupancy probability and their homogeneity values are equal to 1. Otherwise, it is set to 0.
   - Occupancy probability, $P(x,y,l)$. If the cell is homogeneous, $P(x,y,l)$ is equal to the occupancy probability value of any of the four cells immediately underneath. If the cell is not homogeneous, the value of $P(x,y,l)$ is set to a fixed value (c_{NH}).
   - Area, $A(x,y,l)$. It is equal to the addition of the areas of the four cells immediately underneath.
   - Parent link, $(X,Y)_{(x,y,l)}$. If $H(x,y,l)$ is equal to 1, the values of parent link of the four cells immediately underneath are set to (x,y). Otherwise, these four parent links are set to a null value.
   - Centroid, $C(x,y,l)$. It is the centre of mass of the base region associated to (x,y,l).

   After the generation step, remaining nodes present an homogeneity value equal to 1 and provide a quadtree-like discretization. Thus, the complexity of this decomposition is not directly related to the world complexity but to the position of the obstacles.
2. Homogeneous cells fusion. In this step, the algorithm tries to link cells whose parent link values are null. Basically, these cells, (x,y,l), are linked to parents of neighbours cells, $(x_p,y_p,l+1)$, if the following conditions are true:
   - $H(x,y,l) = 1$ & $H(x_p,y_p,l+1) = 1$
   - $P(x,y,l) = P(x_p,y_p,l+1)$
   - $||C(x,y,l) - C(x_p,y_p,l+1)||_2 < DistMax$,
     being $DistMax$ a threshold that fixes the maximum dispersion of the regions at the base.
3. Homogeneous cells classification. Two neighbour cells, (x_1,y_1,l) and (x_2,y_2,l), are fused if the following conditions are true:
   - $(X,Y)_{(x_1,y_1,l)} = NULL$
   - $(X,Y)_{(x_2,y_2,l)} = NULL$
   - $H(x_1,y_1,l) = 1$ & $H(x_2,y_2,l) = 1$
   - $P(x_1,y_1,l) = P(x_2,y_2,l)$
   - $||C(x_1,y_1,l) - C(x_2,y_2,l)||_2 < DistMax$

   When this top-down relinking step is finished, regions linked to a node no longer depend on the layout of the environment. It can be observed that this process only depends on threshold $DistMax$, which is used to select the maximum size of a node. For low $DistMax$s, nodes tend to correspond to large areas. Otherwise, they are related to small areas. Despite this threshold, complicated areas packed with obstacles tend to be related to several nodes rather than to a single one. This is useful to plan paths between pair of nodes because planning is hierarchically decomposed into shorter and easier paths.

It can be noted that this process relies on the split and merge paradigm, but it is significantly faster than conventional 2D split and merge approaches because of the hierarchical nature of the data structure. Fig. 1 shows how nodes are arranged during the bottom-up split stage (Fig. 1.b) and after the top-down merge stage (Fig. 1.c). It can be observed that resulting regions roughly correspond to rooms. Smaller regions are related to occupied areas and, hence, removed from the structure, where only free nodes are allowed.

2.2 Topological map generation

Since homogeneous regions linked to nodes in the proposed structure are connected and roughly correspond to structures like rooms and corridors, such nodes can be used to build a graph. Figs. 2.a-f show levels 1 to 6 of the generated pyramid for the base in Fig. 1.a. Free nodes in those levels are painted in black and the white gaps in the levels correspond to areas where there are no nodes. It can be observed in Fig. 2.f that no nodes are available in levels 6 and above. Only the largest regions in the map are defined at level 5 (Fig. 2.e). Then, the garage and the rooms on the left side of the map are defined at level 4 (Fig. 2.d). Smaller rooms and corridors are mostly defined at level 3 (Fig. 2.c), while minor details appear in lower levels. In order to build a topological map using this structure, nodes in the graph correspond to parentless nodes in the 3D structure. A parentless node in this structure corresponds to a region which is not included in any larger region. For example, the three rooms in the bottom of the map are defined at level 5 (Fig. 2.e), even though they also appear in levels 0 to 4.

Despite the correct distribution of free space, the proposed representation is not valid to build a topological map because obstacle areas corresponding to doors are painted in black in the original map and, hence, assumed to be obstacles. Thus, in the topological representation it would be assumed that a person can not move between two rooms connected by a door because there is no free path between them. Naturally, the map can be manually preprocessed to avoid this problem, but it is easier to use simple image preprocessing to achieve the same results. Fig. 3.a shows the original input map after a gaussian blur is applied. While large obstacles are still clearly dark, thin lines tend to blur to a light grey instead. Then, if a histogram stretching for contrast enhancement is

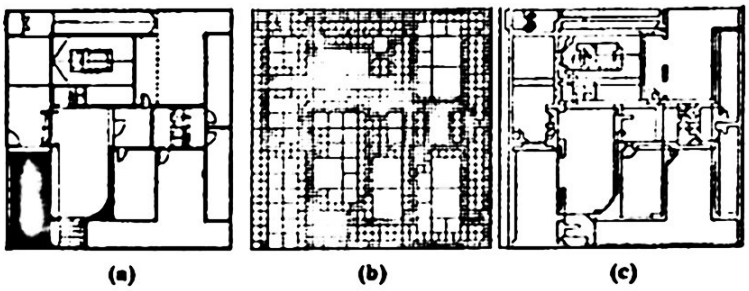

Fig. 1. Structure generation: a) original map; b) hierarchical split; b) hierarchical merge.

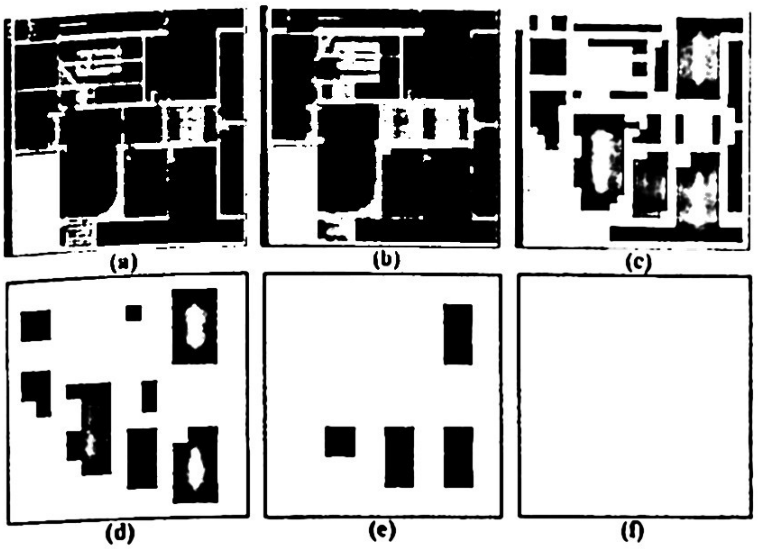

Fig. 2. Map structure: a-f) levels 1 to 6 of the map.

applied, dark areas go black and light areas go white (Fig. 3.b). If the topological map is extracted from Fig. 3.b, doors and thin lines are removed from the base of the structure and connected rooms become linked nodes (Fig. 3.c). It is necessary to note, though, that if a wall is represented by means of a thin line for any reason, it is removed from the map as well, as can be appreciated in the bottom part of Fig. 3.c. Similarly, regions presenting a high density of lines, like the stairs on the right of Fig. 3.c, are also identified as obstacles by the process. This problem can only be solved by correcting the map after generation or by removing such areas by means of texture detection techniques.

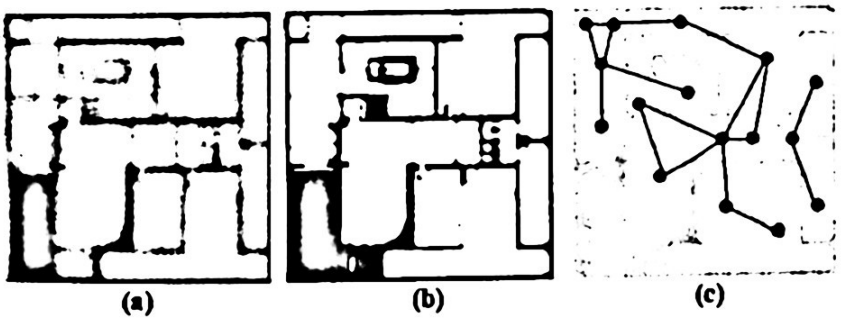

Fig. 3. Map post processing and graph calculation: a) gaussian blur; b) histogram stretching; c) graph calculation.

When the set of nodes in the topological map is available, it is also necessary to build links between them. It can be observed that the proposed data structure implicitly preserves connectivity information: two nodes related to regions in contact at the base must be linked. In order to calculate the weight of the links, the euclidean distance between the centroids of the regions linked to each

pair of nodes are used. This might not be representative if regions could present completely random shapes and, hence, the distance to travel from one to another depended largely on the departure and arrival points, but in the proposed structure regions presenting strange shapes are decomposed into several nodes rather than linked to a single one. It can be noticed that, given a printed map, a person could build a topological map similar to the proposed one fairly fast. The average time to extract a topological map using the proposed technique is 0.45 s. using a conventional Pentium III. However, processing time is not the main advantage of the proposed technique. Its main advantage is that the obtained map is grounded to the metrical map and implicitly adapted to its geometry. Thus, it is extremely easy and fast to calculate paths at low level using the proposed structure, as explained in the next section.

3 Scheduling and navigation

Once a model of the environment is available, scheduling can be performed by simply computing in which order nodes need to be visited. To obtain a complete plan, it is also necessary to know where the mobile is at a given instant, so that the path starts at that position. If the mobile is a human, it can give its approximate position to the system. Otherwise, such a position must be estimated either by active landmark localization (e.g. [7]) or, if the mobile is mechanical, by odometry based localization methods (e.g. [15]). In any case, when nodes to visit are selected, scheduling can be formulated as a TSP: given a finite set of nodes $N = c_1, c_2, ...c_n$ and a distance $d(c_i, c_j)$ for each pair of nodes, the TSP consists of searching for a tour of minimum length to visit all nodes once. N does not include all nodes in the topological map, but only those corresponding to places that need to be visited. Sometimes, the order to visit some places can not be altered (e.g. go to a room and take a patient to the gym). In these cases, we deal with a simple path planning algorithm. In other cases, several rooms must be visited before performing a certain tasks (e.g. collect the medical record of a patient and some equipment before a visit). In these cases, the TSP is used to get the correct visiting order. For n places to visit there are $\frac{(n-1)!}{2}$ tours and, hence, the complexity of the TSP grows very fast with n. However, an exact solution can be calculated when n is low. In our case, n is usually low, so the TSP can be solved exhaustively and time responses at topological level, lower than a second, are more than suitable to operate in real time. Thus, plans can be altered even when an agent is moving. It is necessary to note that, at least in emergency situations, we deal with more than one person. In those cases, the algorithm pre-plans the best routes for all of them so that all important places are visited once: initially the TSP is ran for all persons to visit every room. Using these solutions, we check who reaches any of the goals first, say person P_1. After this, the plan of P_1 is preserved, but the TSP is run for the other persons after removing the goal reached by P_1. It is important to note that this is done a priori, when no one has started to move yet. This operation is performed as many times as necessary until everyone reaches the final goal.

Thus, it is granted that each node is visited only once and tasks are divided into the whole staff or a part of it.

In cases where the mobile is a robotic agent or a person who is not familiar with the environment providing the order in which places should be visited might not be enough. In these cases, it might also be interesting to provide the best path to move between the current position and the next goal at any time. It is important to note that, to solve this problem, the current position of the mobile in the environment is required and it must be either calculated by any of the localization procedures described above or provided by the agent when requested. An efficient path to a given goal can be calculated as follows:

- Calculate which node in the graph the departure point is linked to. This can be done in a straight way because such an information is preserved in the pyramid link structure.
- Calculate a path at topological level between nodes c_i and c_j by means of the well known A* path planning algorithm, being c_i the node related to the current position of the agent and c_j the next destination node in the list returned by the scheduler. This algorithm returns a node path.
- Propagate the node path to base level using the link structure. At this level, the node path becomes a path region which includes the departure and arrival points.
- Using a potential fields approach [19], calculate an unique path at metric level between the departure and arrival points.

Fig. 4 shows an example of the proposed process. Fig. 4.a presents a simple map where a topological graph is over imposed. In this map, a pair of departure and goal points are marked with a "D" and a "G", respectively. After the A* algorithm is used, the path consists of the three nodes marked with a black circle, where the first one is related to "D" and the second one to "G". Fig. 4.b shows the path region after the path is propagated to base level. The potential field approach basically consists of considering obstacles as repulsors and goals as attractors. The direction to follow to the goal at each point of the trajectory is a combination of all forces involved and the final path to the goal is a line of minimum energy. In our case, the path must be included inside the path region, so the boundaries of the path region are considered repulsors and the goal is an attractor. The final path is printed in white in Fig. 4.b and the gradient of the potential field is represented in shades of grey.

4 Test environment

In this work, the mobile agent is a member of the staff of a hospital environment, more specifically the Fondazione IRCCS Santa Lucia, in Rome. The department organization needs the presence of 6 physicians that provide the attendance to 50 patients, 25 beds each 3 physicians, and a chief, plus 6 nurses, divided as well in two halves, and including also a matron and assistant. During the first hours, until 2:00 p.m., the medical staff is almost complete, with the exception

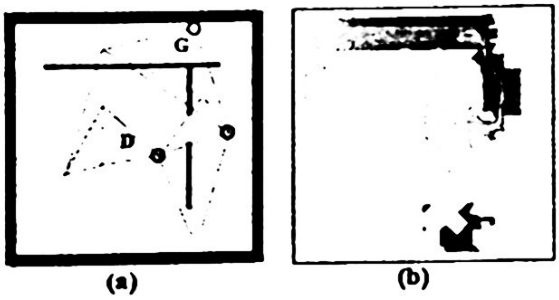

Fig. 4. Hierarchical path planning algorithm

for eventual night services and vacations. From 2:00 to 8:00 p.m. there's only one physician in each department. Finally, during the night there is only one physician in the whole hospital, that includes six departments. Obviously, physicians and nurses dues differ and, of course, every plan is changed in case they have to face an emergency. It can be noted that the squad is not wide and, hence, a better organization and optimization of the resources is required.

In the Fondazione IRCCS Santa Lucia, a standart day consists of the following. Nurses each morning have got to attend the patients considering their needs (wash, change clothes and "catheters", administrating therapy, get vital parameters as blood pressure, body temperature and cardiac frequency, cure pressure ulcers) and, in the end, get the patients up and ready to go to the gymnasium. Of course, this activity must follow a schedule, and the first patients to be ready are the ones first beginning the motory therapy. Physicians visit the patients every morning, after they have been informed about eventual problems occurred during the night, and if this ever happens, this leads to a change to the normal plan. During their visit, physicians can change the therapy and ask for eventual specialist consult for each patient. Every week, each patient has got to be observed by the physician during his training in the gymnasium. Around 12:00, nurses feed patients who are unable to do it self-dependently and administrate drugs. After 2.00 p.m., as aforementioned, there is only one physician in the whole department. He checks blood analysis, eventually change therapies and deals eventual emergencies. At 4:00 p.m. nurses administrate drugs. At 6:00 p.m. nurses feed patients who are unable to do it self-dependently and administrate drugs at 8:00 p.m. In the end, they must attend the patients one more time (wash, change clothes and catheters, administrate therapy, get vital parameters as blood pressure, body temperature and cardiac frequency, care pressure ulcers) and, after this, get the patients ready to go to bed for the night. The last check is at 10:00 p.m.. Then, during the night, they go through an ordinary control monitoring.

When an emergency occurs, the schedules of the whole staff are completely changed. The whole physicians staff comes to the patient room to attend the patient and, to attend its duty, needs to:

- Get there as soon as possible
- Have at least two nurses with him

- Have the emergency trolley and the defribillator near
- Have the oxygen bottle
- Have bandage and everything needed to face eventual injury
- Have a electrocardiograph, sphyigmometer and saturimeter
- Have the patient medical record containing all his information, because he might not be familiar with that specific patient if he/she is not his personal physician during the afternoon or the night attendance.

Each of the aforementioned elements required by the physician to face the emergency are located in different places, and can even be moved during the day. Specifically, there is only one emergency trolley and defibrillator in each department, located in one of the two medical rooms (usually predefined) unless it's been recently used in the other half of the department. The oxygen bottle is placed in the medical room as well. Bandages are placed in both medical rooms. Sphyigmometer is placed in both rooms. There is only one electrocardiograph and saturimeter in each department, located in one of the two medical rooms (usually predefined) unless it's been recently used in the other half of the department. The medical records are placed in the physician's room during the morning and in the nurses room during the afternoon and during the night.

Naturally, such a complex system works well when the medical and the nurses staff has worked together for a long time, when everything is placed in the right place, and when there are no critic situations such as double emergencies. It is also inmediate to realize that the staff can go through different troubles due to "ambient obstacles" and to the fact that physicians and nurses may not know very well where to move rather than how to move. All this leads to a waste of resources that could be better used and distributed during an ordinary day and to less speed and efficiency in the attendance to a patient during an emergency. This delay, even if it does not worse his prognosis, certainly makes patients suffer and provoke anxiety. In the end, a proper use of the stuff grants the patients a better care.

5 Experiments and results

This section includes several results of the proposed scheduling strategy. First, a topological map of the hospital is extracted from its plot as proposed (Fig. 5). This process takes 0.45 s. approximately. There are several important rooms in this plant: Medical Rooms 1 and 2 (MR1 and MR2), Nurses Rooms 1 and 2 (NR1 and NR2), the Physician Room (PR), the gym, the dining room (DR) and rooms 301 to 327 (R301-R327). As previously commented, some equipment is located only in one of the medical rooms, in these tests MR1.

During an ordinary day, the matron decides in which order the patients must visit the gym. This influences the order in which a given nurse, which has different patients assigned, must attend them and take them there. Leaving factors not related to navigation aside, in order to provide a suitable gym scheduling, the matron must take into account where the patient assigned to a nurse are to determine in which order they must be visited. In a first test, we have chosen

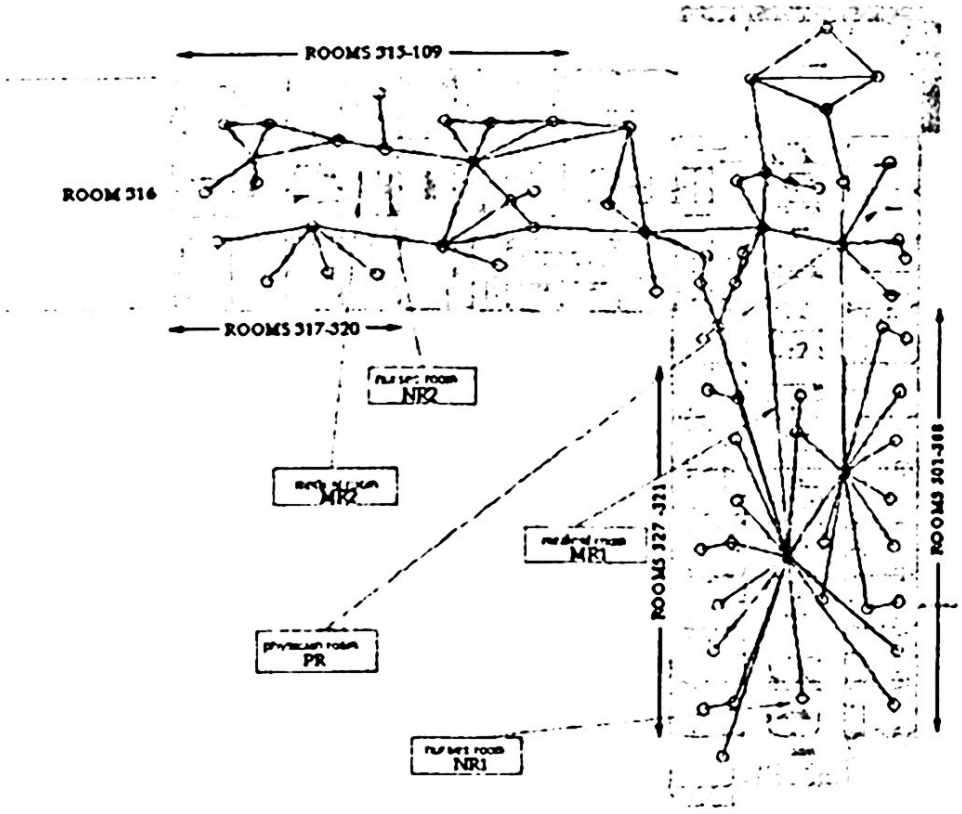

Fig. 5. Original map with its topological map overimposed

nurse who is assigned to patients in rooms R301, R308, R323 and R327. We assume that, originally, the nurse will be at NR1. In our experiment, she must go to each room, attend the patient there, take him to the gym, wait for him there, bring him back to his room and proceed to the next patient. Obviously, these basic actions may change to suit the structure of the hospital organization. After the TSP is used, the visiting order is R327, R323, R308 and R301. When the nurse reaches each room, she attends the patient and then, she receives the fastest route to the gym and back. Fig. 6.a shows a path to go the gym and back from R301. In this case, it would probably have been more optimal to use the east corridor, but heuristical planning algorithms do not grant the optimal solution. Similarly, Fig. 6.b shows a path to move from R308 to DR and back. In this case, the path does seem to be the shortest one. Finally, Fig. 6.c shows a monitoring visiting order for the night, where the proposed scheduling sequence used. Again, in this case paths seem to be qualitatively adequate.

It must be observed that the problem becomes more complex when there are more rooms to monitor per nurse and when additional criteria (e.g. time spent with a patient, nurses assisting other patients while one is busy in the gym, etc) need to be considered. In this paper, though, we only regard navigation factors. However, one of these factors is how to react when a planned path is blocked by unexpected factor. Fig. 7 shows a typical example of one of those

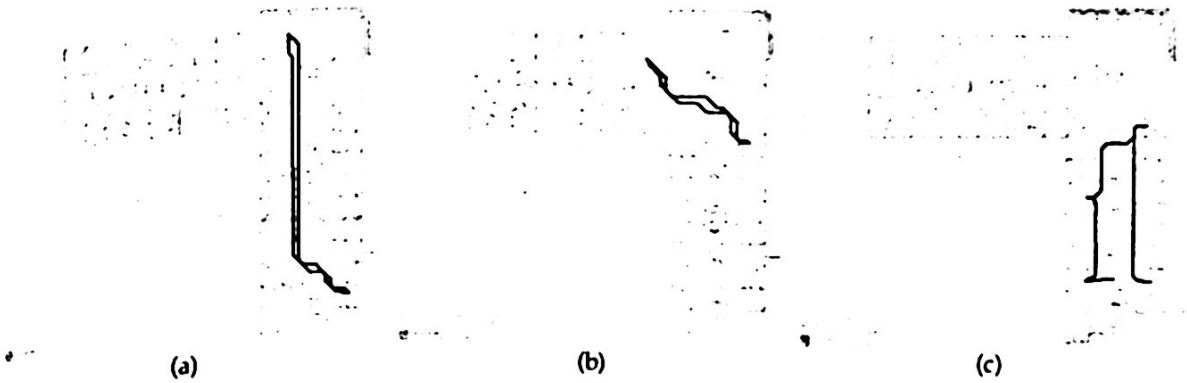

Fig. 6. Path planning during an ordinary day: a) path from R301 to the gym and back; b) path from R308 to DR and back; c) path to monitor R327, R323, R308 and R301 efficiently.

replanning problems. In the original topological map, the link marked in Fig. 7.a joining nodes in both corridors in the east wing of the plant existed. Then, a path running from one wing of the plant to the other went through that area (Fig. 7.b). However, in a new experiment, the link vanishes due to an ambient obstacle and both corridors are no longer connected at the wing junction. The recalculated topological map is very similar to the previous one, as expected, minus the aforementioned link. Thus, in this case, an alternative path joining both wings in an efficient way does necessarily run through the gym (Fig. 7.c). Figs. 7.b and c show both paths returned by the potential fields overimposed to the path regions returned by the high level planner. It is important to note that paths can be calculated as fast as 0.05 s average over the used map. Thus, as soon as the obstacle in the way is detected, an alternative path can be provided.

A more interesting test is when an emergency situation at night is presented. In this situation, there are only two nurses at R307 (Nurse1) and R324 (Nurse2) and a doctor (Doctor) at R314. Then, an emergency is detected at R312. The emergency trolley, defibrillator and other unique equipment is supposed to be at MR1. Medical records are at NR2 at night. The rest of the equipment is located both at MR1 and MR2. Thus, a complete route for a single person would include its position, medical room 1 (MR1), nurses room 2 (NR2) and room 312. Naturally, the TSP can return an exact solution with so few nodes. Results, presented in table 1, were to be expected. All distances are expresed in resolution units. For each run of the algorithm, places in the plans finally expected to be visited by a given member of the staff are bolded. Nurse1 is closer to MR1 and would reach it first (Run 1), so Doctor and Nurse2 do not even try that node. When we recalculate routes taking this fact into account (Run 2), it is obvious that the doctor is closer to NR2, where the records are. Thus, Nurse1 and Nurse2 do not try to visit NR2 and go to room 312 straightly. The final paths for the members of the staff are NR2, 312, MR1,312 and 312 for the doctor and nurses 1 and 2, respectively (Fig. 8). It can be checked that each room is visited only once, that at the end the doctor and 2 nurses are at room 312

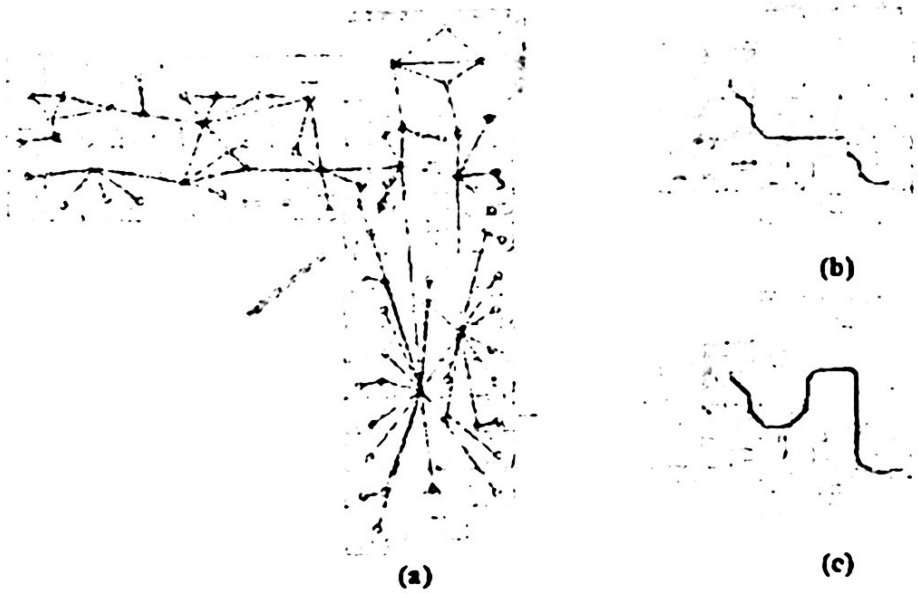

Fig. 7. Original map with its topological map overimposed

R312), as required and that the lengths of their paths, if not the best because of the heuristical nature of the path planning algorithm, are clearly optimized.

is interesting to note that the length of the path for Nurse1 does not change nuch whether she has to visit NR2 or not. This happens because the fastest path to reach R312 runs through NR2 (Fig. 8.b). Test 2 deals with an additional problem: the equipment supposed to be in MR1 has in fact been moved to MR2 and, hence, when Nurse1 arrives there, she asks for a change of plans. The staff has started to move and Doctor and Nurse 2 are on their way to NR2 and R312 respectively. It can be observed in the table that they are redirected. Now the Doctor gathers all equipment, first in MR2 and then in NR2, and both nurses go straightly to R312. In this test, both nurses save the time of visiting MR2, which visited by the doctor instead. It needs to be noted that in this case, all people has already moved 86 units, required by Nurse1 to reach MR1. Hence, the real final distances are 310, 699 and 635 respectively. As expected, the doctor path is longer than before, because he has to change his plans and move to MR2 as well. However, the nurses' paths are quite similar because they are not supposed to go to MR2 and the rest of the plan, going to R312, matches their previous ones.

It can be observed that, for such a reduced number of nodes and using no high level constraints, the proposed problem is relatively easy to solve. However, the proposed data structure and planning algorithms are also suitable for larger problem instances and, so, they can provide the basis to solve complex problems as well.

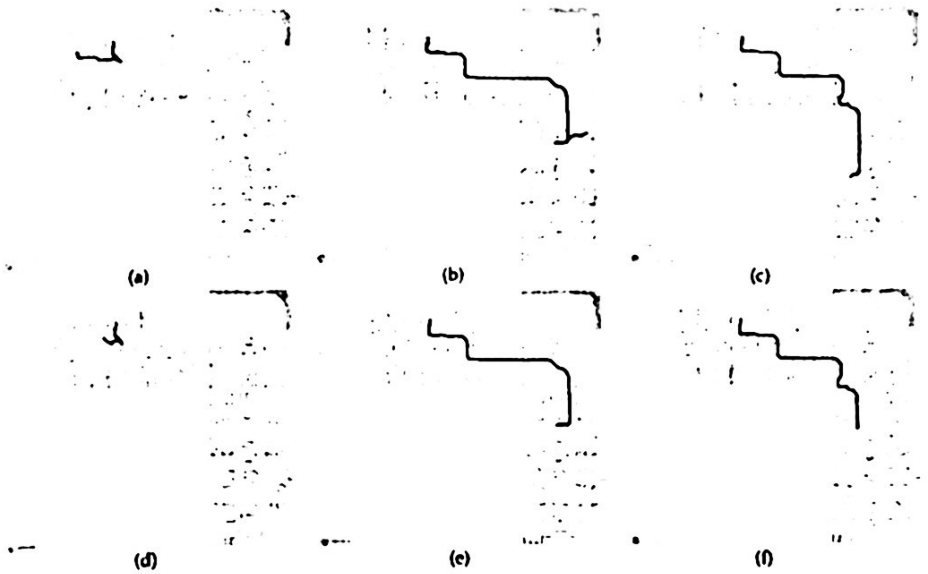

Fig. 8. Paths to attend emergency in room 312 for Dortor, Nursel and Nurse 2 in a-c) Test 1; and d-f) Test 2.

6 Conclusions and future work

This paper has presented a new data structure to extract a topological map from a hospital plant so that scheduling can be performed in a fast way. We have also presented a path planning technique to provide an efficient route to reach the goals in the schedule, so that members of the staff less familiarized with the environment can optimize their work. Both the topological map generation and the calculation of the paths are fast enough to adapt to unexpected obstacles and situations. Tests have been performed in a plant of the Fondazione IRCCS Santa Lucia, in Rome. Results have proven that fast scheduling can be achieved, that people can be efficiently coordinated in emergencies and that paths provided by the scheduler are realistic and efficient as well. However, it is assumed that a centralized scheduling system capable of communicating with each member of the staff is available. Under this premise, a person does not need to know where the others are, but simply follow the guidelines provided by the scheduler that include which places to visit, in which order and how to reach every one of them.

Future work will focus on improving interaction with other users for a better job coordination during an ordinary day. Besides, more environment intelligence is required to: i) determine if some rooms (e.g. medical or nurse rooms) can not be crossed to shorten a path; ii) determine if there is room for large objects (e.g. wheelchairs) to move through a place; iii) include in our calculations how difficult it is to cross a place (e.g. when it is crowded) to provide alternative routes; iv) take into account how many members of the staff are required to move the equipment so that rooms can be visited by several people rather than one (e.g. nursel:move to medical room 1 and take the emergency trolley; nurse2:move to medical room 1 and take the defibrillator). Also, the proposed method will be adapted to an autonomous agent to build an intelligent wheelchair.

	Test 1	
	Run 1	Total Distance
Doctor	MR1 (675), NR2 (496), R312 (113)	1284
Nurse1	MR1 (86), NR2 (496), R312 (113))	695
Nurse2	MR1 (120), NR2 (496), R312 (113)	729
	Run 2	Total Distance
Doctor	NR2 (180), R312 (113)	293
Nurse1	MR1 (86), NR2 (496), R312 (113)	695
Nurse2	NR2 (522), R312 (113)	635
	Final Path	Total Distance
Doctor	NR2 (180) R312 (113)	293
Nurse1	MR1 (86) R312 (608)	694
Nurse2	R312 (634)	634
	Test 2	
	Run 2'	Total Distance
Doctor	MR2 (22), NR2 (89), R312(113)	224
Nurse1	NR2 (496), MR2 (89), R312 (57)	642
Nurse2	NR2 (433), MR2 (89) , R312 (57)	568
	Run 3'	Total Distance
Doctor	MR2 (22), NR2 (89), R312(113)	224
Nurse1	NR2 (496), R312 (113)	609
Nurse2	NR2 (433), R312 (113)	546
	Final Path	Total Distance
Doctor	MR2 (22), NR2 (89), R312(113)	224
Nurse1	R312 (608)	608
Nurse2	R312 (545)	545

Table 1. Places visited by the hospital staff plus distances during the described emergency when the equipment is where it was expected (Test 1) and otherwise (Test 2)

Acknowledgments

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Computers in Imaging and Guided Surgery

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1. Introduction

The growing demand for complex and minimally invasive surgical interventions is driving the search for ways to use computer-based information technology as a link between the pre-operative plan and the tools utilized by the surgeon. Computers, used in conjunction with advanced surgical assist devices, will fundamentally alter the way that are procedures are carried out in 21st Century operating rooms.

Computer Integrated Surgery (CIS) systems make it possible to carry out surgical interventions that are more precise and less invasive than conventional procedures, while judiciously tracking and logging all relevant data. This data logging, coupled with appropriate tracking of patient outcomes, will make possible a totally new level of quantitative patient outcome assessment and treatment improvement analogous to "total quality management" in manufacturing.

The goals of CIS systems are to enhance the dexterity, visual feedback, and information integration of the surgeon. While medical equipment is currently available to assist the surgeons in specific tasks, it is the synergy between these capabilities that gives rise to a new paradigm. The goal is to complement and enhance the surgeon's skills and always leave him in control, never to replace him.

CIS systems are instances of an emerging paradigm of human-computer cooperation to accomplish delicate and difficult tasks. In some cases, the surgeon will supervise a CIS system that carries out a specific treatment step such as inserting a needle or machining bone. In other cases, the CIS system will provide information to assist the surgeon's manual execution of a task, for example through the use of computer graphic overlays on the surgeon's field of view. In some cases, these modes will be combined.

From an engineering systems perspective, the objective can be defined in terms of two inter-related concepts:

- ***Surgical CAD/CAM systems*** transform preoperative images and other information into models of individual patients, assist clinicians in developing an optimized interventional plan, register this preoperative data to the patient in the operating room, and then use a variety of appropriate means, such as robots and image overlay displays, to assist in the accurate execution of the planned interventions.

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- ***Surgical assistant systems*** work interactively with surgeons to extend human capabilities in carrying out a variety of surgical tasks. They have many of the same components as Surgical CAD/CAM systems, but the emphasis is on intraoperative decision support and skill enhancement, rather than careful pre-planning and accurate execution.

Table 1 summarizes the main factors that must be considered in assessing the value of CIS systems with respect to their potential application.

Advantage	Important to whom	How quantify	Summary of key leverage
New treatment options	Clinical researchers Patients	Clinical and pre-clinical trials	Transcend human sensory-motor limits (e.g., in microsurgery). Enable less invasive procedures with real time image feedback (e.g., fluoroscopic or MRI-guided liver or prostate therapy). Speed clinical research through greater consistency and data gathering.
Quality	Surgeons Patients	Clinician judgment; Revision rates	Significantly improve the quality of surgical technique (e.g., in microvascular anastomosis), thus improving results and reducing the need for revision surgery
Time and cost	Surgeons Hospitals Insurers	Hours, Hospital charges	Speed OR time for some interventions. Reduce costs from healing time and revision surgery. Provide effective intervention to treat patient condition.
Less invasiveness	Surgeons Patients	Qualitative judgment; recovery times	Provide crucial information and feedback needed to reduce the invasiveness of surgical procedures, thus reducing infection risk, recovery times and costs (e.g., percutaneous spine surgery).
Safety	Surgeons Patients	Complication & revision surgery rates	Reduce surgical complications and errors, again lowering costs, improving outcomes and shortening hospital stays (e.g., robotic THR, steady hand brain surgery).
Real time feedback	Surgeons	Qualitative assessment Quantitative comparison of plan to observation Revision surgery rates	Integrate preoperative models and intraoperative images to give surgeon timely and accurate about the patient and intervention (e.g., fluoroscopic x-rays without surgeon exposure, percutaneous therapy in conventional MRI scanners). Assure that the planned intervention has in fact been accomplished
Accuracy or precision	Surgeons	Quantitative comparison of plan to actual	Significantly improve the accuracy of therapy dose pattern delivery and tissue manipulation tasks (e.g., solid organ therapy, microsurgery, robotic bone machining).
Documentation and follow-up	Surgeons Clinical researchers	Data bases, anatomical atlases, images, and clinical observations	CIS systems inherently have the ability to log more varied and detailed information about each surgical case than is practical in conventional manual surgery. Over time, this ability, coupled with CIS systems' consistency, has the potential to significantly improve surgical practice and shorten research trials.

Table 1: Key advantages from CIS Systems.

The CIS paradigm started to emerge from research laboratories in the mid-eighties, with the introduction of the first commercial navigation and robotic systems in the mid-nineties. Since then, a few hundreds of CIS systems have been installed in hospitals and are in routine clinical use, and a few tens of thousands of patients have been treated, with their number rapidly growing. The clinical areas for which these systems have been developed are neurosurgery, orthopedics, radiation therapy, and laparoscopy. Preliminary evaluation and short-term clinical studies indicate improved planning, execution precision, which results in a reduction of complications and shorter hospital stays. However, some of these systems have in some cases a steep learning curve and longer intraoperative times than traditional procedures, indicating the need to improve them.

The key technical enabling factors that promoted the development of these systems were the increasing availability of powerful imaging modalities, such as CT, MRI, NMT, and live video, powerful computers with graphics capabilities, novel algorithms for model construction and navigation, and integrative systems and protocol development. This article reviews the main technical issues of CIS systems. It is organized as follows: the next section briefly describes two CIS systems. The following section presents an overview of CIS systems, their main elements architecture, and information flow. The following section summarizes the main enabling technologies of CIS systems: imaging and tracking, modeling and analysis, robotics and sensing, man-machine interfaces, and systems integration technology. We conclude with a review on the state of the art and possible directions for development.

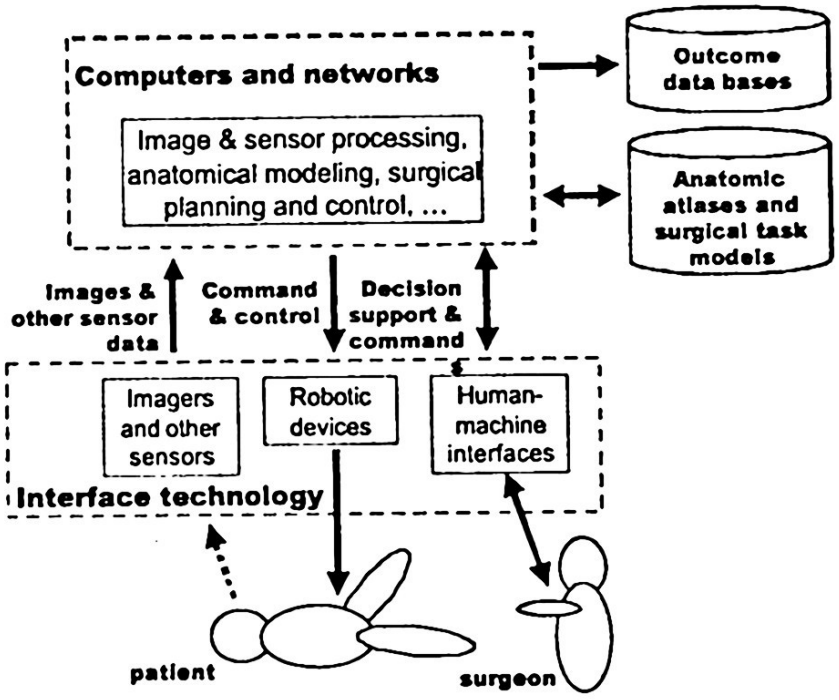

Figure 1: The architecture of CIS systems: elements and interfaces

2. The structure of CIS systems

Figure 1 illustrates the key system elements and interfaces of CIS systems. At the core is a computer (or network of computers) running a variety of modeling and analysis processes, including image and sensor processing, creation and manipulation of patient-specific anatomical models, surgical planning, visualization, monitoring and control of surgical processes. These processes receive information about the patient from medical imaging devices about the patient and may directly act on the patient through the use of specialized robots or other therapy devices controlled by the computer. They also communicate with the surgeon through a variety of visualization subsystems, haptic devices, or other human-machine interfaces. The surgeon remains in overall control of the procedure and, indeed, may do all of the actual manipulation of the patient using hand tools with information and decision support from the computer. The modeling and analysis processes within the computer will often rely upon databases of a priori information, such as anatomical atlases, implanted device design data, or descriptions of common surgical tasks or sub-tasks. The computer also has the ability to retain essentially all information developed during surgical planning and execution and store it for post-operative analysis and comparison with long term outcomes.

Devices and techniques to provide the interfaces between the "virtual reality" of computer models and surgical plans to the "actual reality" of the operating room, patients, and surgeons are essential elements of CIS. Broadly, we recognize three inter-related categories of interface technology:

Imaging techniques and sensory devices: Novel sensors and imaging methods are needed to improve the information available about patients.

Robotic devices and systems: Advances are needed in surgically suitable devices and control methods that extend human precision, geometric accuracy, and ability to work in confined spaces.

Human-machine interfaces: Advances are needed in human-machine communication devices, including haptic interfaces and superimposed visual displays.

Research in these areas draws on a broad spectrum of "core" engineering research disciplines, including materials science, mechanical engineering, control theory, device physics, and others. The fundamental challenge is to extend the sensory, motor, and human-adaptation abilities of computer-based systems in a demanding and constrained environment. Particular needs include compactness, precision, biocompatibility, imager compatibility, dexterity, sterility, and human factors.

Figure 2 illustrates the overall information flow of computer-integrated surgical systems from the perspective of the surgical CAD/CAM paradigm. These systems combine preoperative and intraoperative modeling and planning with computer-assisted execution and assessment. The structure of Surgical Assistant systems is similar, except that many more decisions are made intraoperatively, and preoperative models and plans may sometimes be relatively less important. CIS applications can be thought of as comprising three phrases:

- ***Preoperative: phase:*** A surgical plan is developed from a patient-specific model generated from preoperative images and *a priori* information about human anatomy contained in an anatomical atlas or database. Planning is highly application-dependent since the surgical procedures are greatly different. In some cases, it may be a relatively straightforward interactive simulations or selection of some key target positions, such as performing a tumor

biopsy in neurosurgery. In other cases, such as in craneo-facial surgery, planning can require sophisticated optimizations incorporating tissue characteristics, biomechanics, or other information contained in the atlas and adapted to the patient-specific model.

- *Intraoperative phase:* The images, patient-specific model, and plan information are brought into the operating room and registered to the patient, based on information from a variety of sensors, usually including a 3D localization system and/or imaging device. In some cases, the model and plan may be further updated, based on the images. The computer then uses a variety of interface devices to assist the surgeon in execution of the surgical plan. Depending on what is most appropriate for the application these interfaces may include active devices such as robots, "smart" hand tools, and information displays. As the surgery proceeds, additional images or other measurements may be taken to assess progress and provide feedback for controlling tools and therapy delivery. Based on this feedback, the patient model may be updated during the procedure, and this updated model may be used to refine or update the surgical plan to ensure that the desired goals are met. Ideally, intraoperative imaging and other feedback can ensure that the technical goals of the surgical intervention have been achieved before the patient leaves the operating room. Further, the computer can identify and record a complete record of pertinent information about the procedure without significant additional cost or overhead.
- *Postoperative phase:* The preoperative and intraoperative information are combined with additional images and tests, both to further verify the technical results of the procedure and to assess the longer-term clinical results for the patient. Further, the results of many procedures may be registered back to an anatomical atlas to facilitate statistical studies relating surgical technique to clinical outcomes.

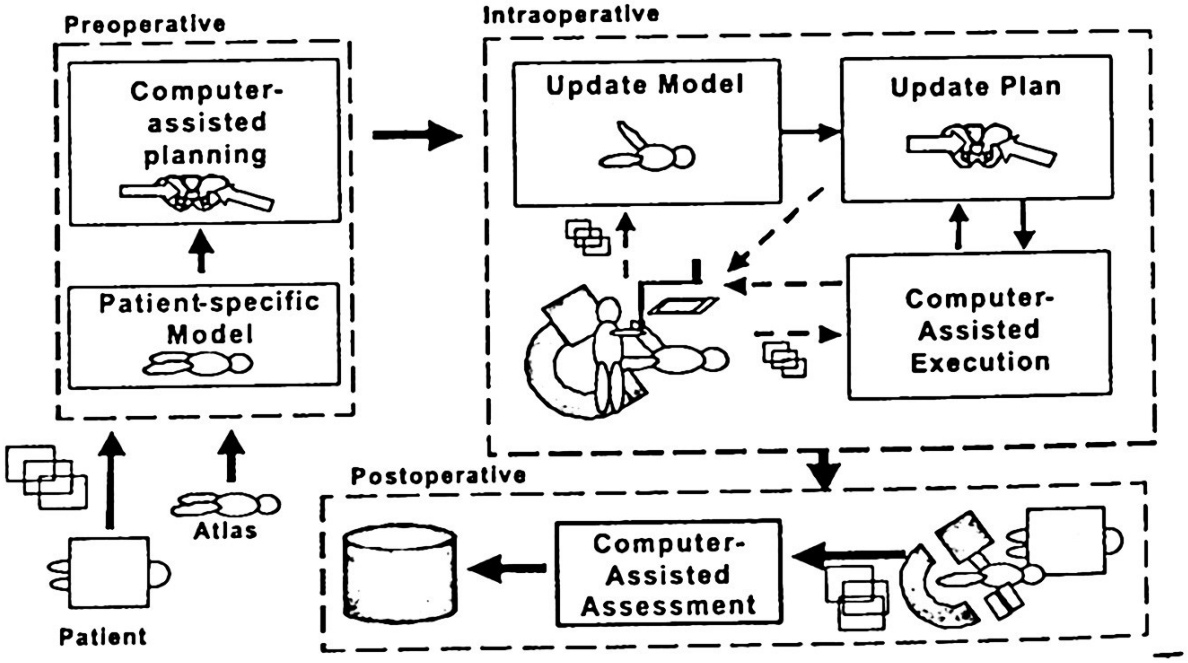

Figure 2: Major information interfaces in CIS systems

Note that the above description is of a generic CIS system, as actual systems do not necessarily require all these capabilities. Also, some of these capabilities are beyond the current state of the art.

From a surgeon's perspective the key difference between advanced medical equipment and CIS systems is the information integration, both between phases and within each phase. This new capability requires in most cases modifications to existing surgical protocols, and in a few cases radically new protocols. It could also enable more surgeons to perform certain difficult procedures that require much coordination and knowledge available to only a few experienced specialists, or perform procedures that are currently not feasible.

3. Examples of computer-integrated surgery systems

3.1 Surgical CAD/CAM systems

Robotic Joint Surgery: The ROBODOC® [1-5] system was developed clinically by Integrated Surgical Systems from a prototype developed at the IBM T.J. Watson Research Center in the late eighties (Figure 1). Both ROBODOC and a very similar subsequently introduced called CASPAR [6] were originally applied for cementless primary total hip replacement surgery, although other applications, notably total knee replacement surgery [7-9] and revision hip surgery [10, 11], have subsequently been introduced. In primary total hip replacement procedures, a damaged joint connecting the hip and the femur is replaced by a metallic implant inserted into a canal broached in the femur. The goal of ROBODOC is to reduce the complications associated with canal broaching, and improve the surface finish of the canal for a better implant fit.

ROBODOC allows surgeons to plan preoperatively the procedure by selecting and positioning an implant with respect to a Computer Tomography (CT) study and intraoperatively mill the corresponding canal in the femur with a high-speed tool controlled by a robotic arm. It consists of interactive preoperative planning software, called ORTHODOC, and an active robotic system for intraoperative execution. Preclinical testing showed an order-of-magnitude improvement in precision and repeatability in preparing the implant cavity. As of Fall, 2000, 17 systems were in clinical use, having performed over 6,000 procedures, with no serious complications due to the robot and very positive results reported (e.g., [8, 12-14].

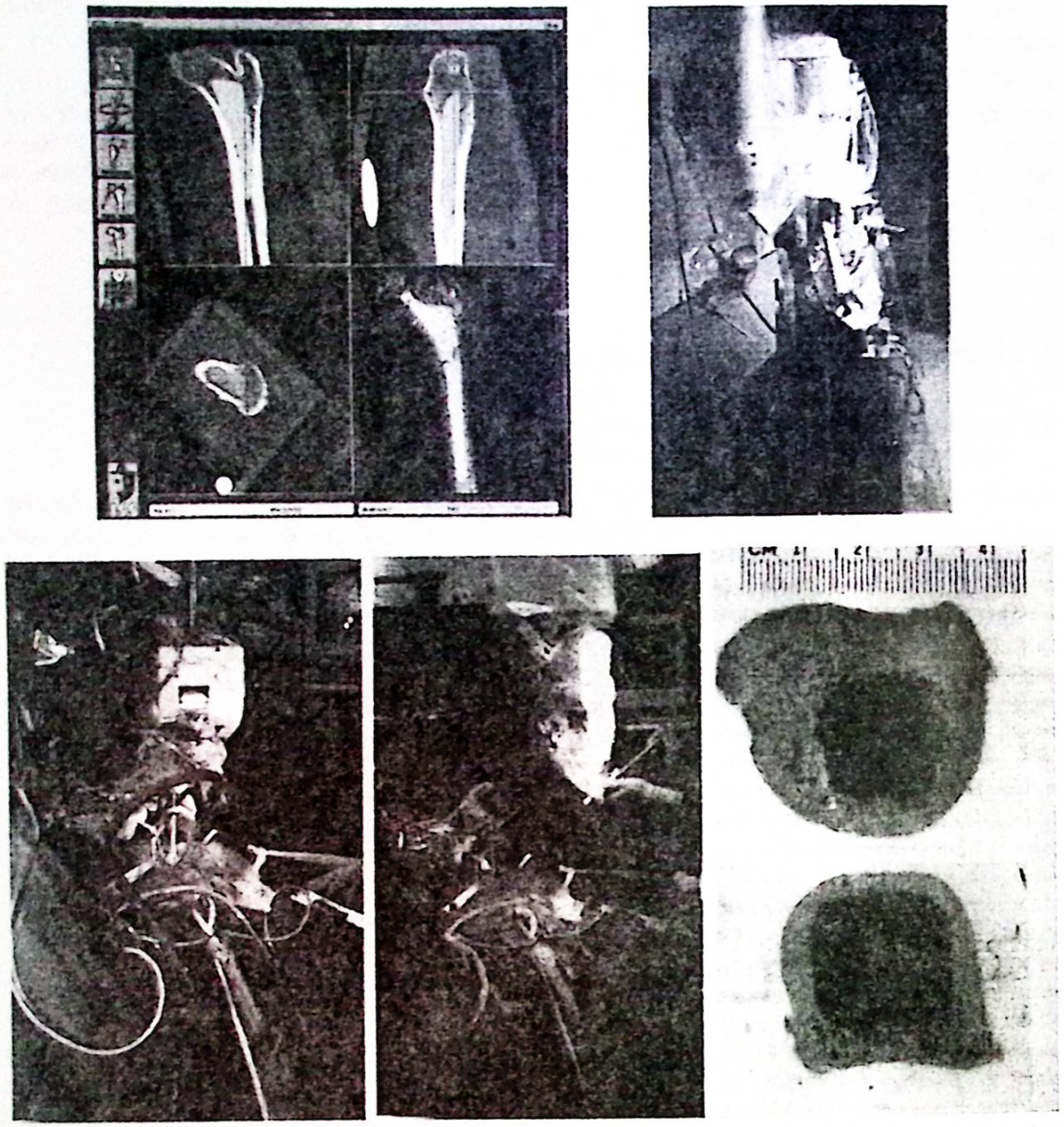

Figure 3: The ROBODOC system. The top left figure shows a screen of ORTHODOC, the preoperative planning module. Three windows show orthogonal cross sections of the CT and one shows a three-dimensional reconstruction of the femur. The yellow shape is the implant, which is chosen and positioned by the surgeon before the surgery. The top right figure shows the six-axis robot covered by a sterile protection drape. The machining tool (center) is inclined to provide better access to the patient trochanter. In the bottom left and center, the ROBODOC system in action: the surgeon attaching the milling tool to the robot after patient preparation (lleft), and in the robot milling the femoral canal (center). The bottom left image shows cross sections of a manually broached femur (top) and a robotically machined femur (bottom), which has superior surface finish and fit.

Other robotic systems have been proposed or (in a few cases) applied for hip or knee surgery include [15-21]. Navigation-assisted systems relying on surgeons' manual manipulation of surgical instruments have been applied extensively in the spine (e.g., [22-24]), pelvis (e.g., [25, 26], fractures (e.g., [27-31], hip (e.g., [32-34]), and knee (e.g., [35-38]).

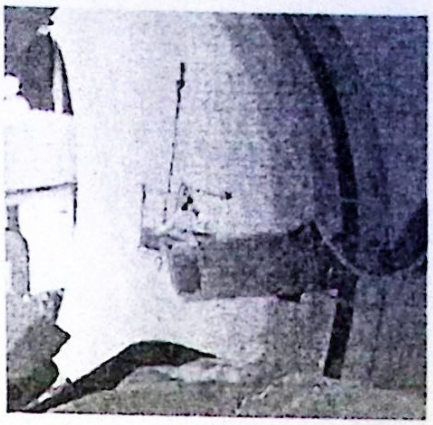

Figure 4: Remote-center-of-motion robot with in-CT injection system. Fiducial markers on the driver enable localization of the needle from a single CT image.

Percutaneous Therapy: One of the first uses of robots in surgery was positioning of needle guides in stereotactic neurosurgery [39-41]. This is a natural application, since the skull provides rigid frame-of-reference. However, the potential application of localized therapy is much broader, and a number of groups are pursuing efforts to extend the use of image-guided, robotically-assisted percutaneous therapy to other parts of the body. Work at Johns Hopkins is typical of this activity. One early experimental system [42, 43] was used to establish the feasibility of inserting radiation therapy seeds into the liver under biplane xray guidance. In this work, small pellets were implanted preoperatively and located in CT images used to plan the pattern of therapy seeds. After this experiment and related work directed at placing needles into the kidney [44, 45] established the basic feasibility of this approach, subsequent work focused on the development of a modular family of robots for use in a variety of imaging and surgical environments. Figure 4 shows an elegant compact remote-center-of-motion device (RCM) developed by Stoianovici *et al.*[46], together with a novel end-effector developed by Susil, Masamune *et al.* that permits the computer to determine the needle pose to be computed with respect to a CT or MRI scanner using a single image slice [47, 48]. This arrangement can have significant advantages in reducing set-up costs and time for in-scanner procedures and also eliminates many sources of geometric error.

3.2 Surgical Assistant Systems

Navigation Systems: Surgical navigation systems (e.g., [49, 50] and *supra*) may be thought of either as "surgical assistants" providing useful information to a surgeon or (as mentioned above) as instruments assisting in the execution of procedures planned from preoperative models. These systems are widely deployed and their use rapidly becoming the standard-of-care in brain surgery and certain spine procedures. Figure 5 shows a typical system, in this case the StealthStation® is [51] manufactured by Medtronic Surgical

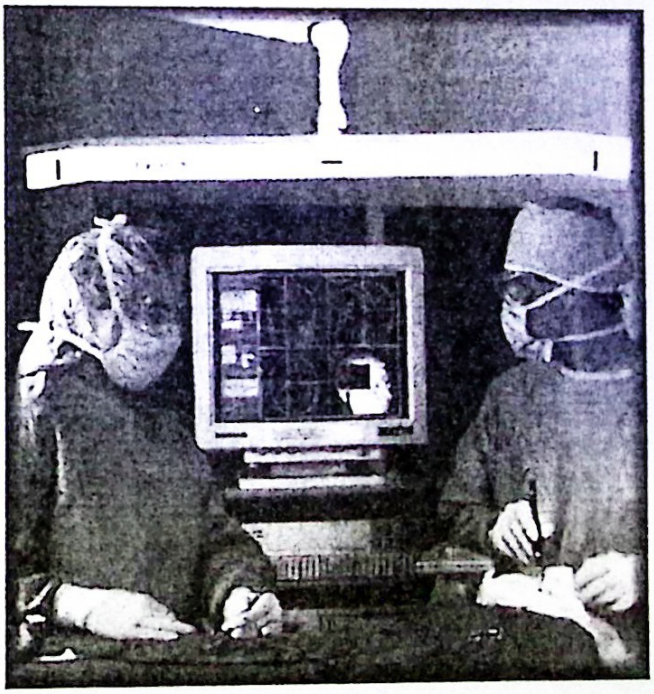

Figure 5: A CIS navigation system in action. (Photo courtesy Medronic Surgical Navication Technologies)

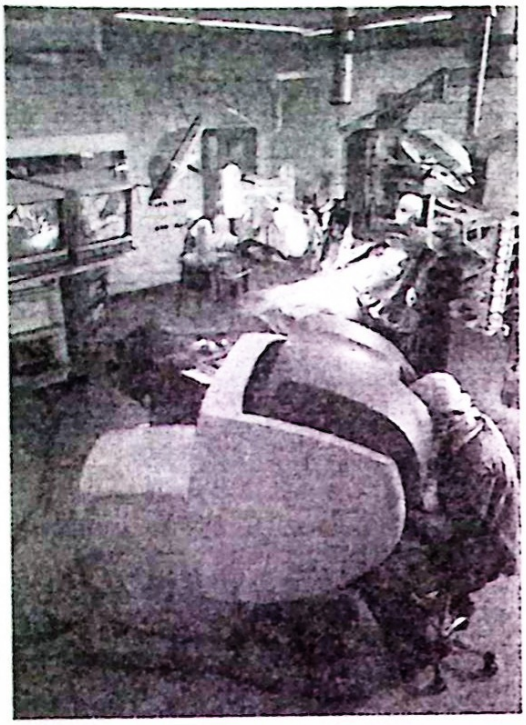

Figure 6: Telesurgical robot for laparoscopic surgery (Photo courtesy Intuitive Surgical).

Navigation Technologies. The system allows surgeons to intraoperatively visualize in real time the relative locations of surgical tools and anatomy and perform surgical actions accordingly. The anatomical model used for navigation is constructed from preoperative CT or MRI data. The instruments and rigid anatomy location is obtained in real time by attaching to them frames with light-emitting diodes that are accurately tracked with a stereoscopic optical tracking camera. The preoperative model is registered to the intraoperative situation by touching with a tracked proble predefined landmarks or points on the anatomy surface and matching them to their corresponding location on the model. Intraoperative navigation allows for less invasive surgery and more precise localization without the need of repeated intraoperative X-ray or ultrasound two-dimensional imaging. For example, to perform a biopsy of a tumor on the brain, the surgeon directs the instrumented drill on the patient's skull with the help of the images, and drills directly towards the tumor instead of making an incision on the skull and visually looking for the tumor.

Robotic assistants: Surgical assistant robots can be used to enhance human performance or efficiency in surgery. Much of the past and current work on assistants (e.g., [52-56]) has emphasized teleoperation. Figure 6 shows a typical telesurgical system, in this case the Intuitive Surgical DaVinci™ system.

Another approach which has been developed extensively by the CIS group at Johns Hopkins, and that has also been explored independently by Davies, et al. [17, 18, 60] emphasizes cooperative manipulation, in which the surgeon and robot both hold the surgical tool. The robot senses forces exerted on the tool by the surgeon and moves to comply. Initial experiences with this mode in Robodoc and subsequently with the IBM/JHU LARS system [61-65] indicated that it was very popular with surgeons and offered means to augment human performance while maximizing the surgeon's natural hand-eye coordination within a surgical task. Subsequent work at Johns Hopkins has focused on extending this work into microsurgery [57, 58, 66]. This work has included both extension of the basic cooperative control paradigm to close compliance loops on a scaled combination of forces exerted by the surgeon and tissue interaction forces [57, 59], as well as based on other sensors such as visual processing.

Other systems are commonly used for mundane tasks such as manipulating endoscopes [61, 67, 68] or surgical retraction [69]. More recently, there has been interest in developing similar systems for use with ultrasound [70-72]. Figure 8 shows one such example.

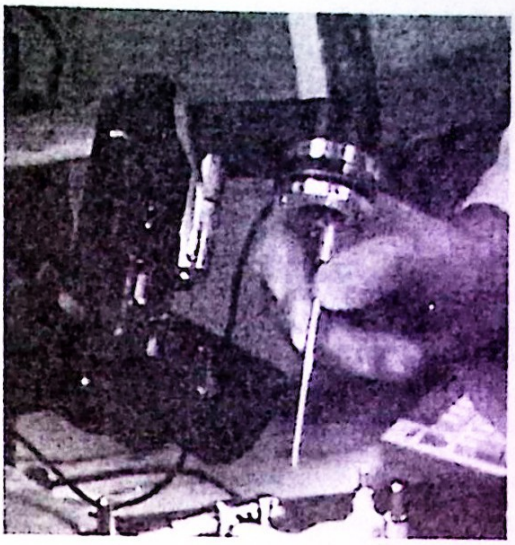

Figure 7: JHU "Steady Hand" microsurgical assistant robot [57-59]

4. The future of computer-integrated surgery

The development of innovative CIS systems has seen a boom in the last ten years, and we expect this to continue in the future. Together with the technological advancements, we see more short and mid-term clinical studies that evaluate the clinical benefits and cost-effectiveness of the methods. We believe that this new paradigm is here to stay.

We predict that computer-integrated surgery will have the same impact on health care in the coming decades that computer-integrated manufacturing has had on industrial production in the recent past. Computer-integrated manufacturing introduced an unprecedented level of information integration across all processes of product design and manufacturing, from early design to recycling and disposal. It brought with it total information and quality management, which made a qualitative difference. We see this happening

Achieving this vision will require both significant advances in basic engineering knowledge and the development of robust, flexible systems that make this knowledge usable in real clinical application.

It is important to remember that the ultimate payoff for CIS systems will be in improved and more cost-effective health care. Quantifying these advantages in practice can be problematic, and sometimes the final answer may take years to be demonstrated. The consistency, enhanced data logging, and analysis made possible by CIS systems may help in this process. It will not be easy to figure out how to apply these capabilities.

There is a need for novel algorithms and representational methods for modeling the patient and surgical environment and for using this information in the planning and execution of surgical procedures. Issues of image processing, modeling and analysis are ubiquitous in computer-integrated surgical systems. Advances are needed in each of the topics (registration, segmentation, etc.) enumerated there. Fundamental themes underlying this research include: 1) extracting and combining information from multiple sources and sensors; 2) combining functional and geometric information; 3) representing and reasoning about uncertainty; and 4) managing complexity. Further, it is necessary to develop methods that are computationally effective, i.e., that enable our surgical planning and execution systems to extract and apply useful information to specific tasks in a timely fashion. Of particular interest for much of our research over the next few years will be development of near-real time methods for segmenting intraoperative images and adapting them to prior patient models derived from preoperative images and/or anatomical atlases.

5. Acknowledgments

Any survey or critical summary must necessarily draw upon the work of many people. We would like especially to acknowledge the contributions of many colleagues over the past decade who have helped develop an evolving shared understanding of medical robotics and computer-integrated surgery. We are especially grateful to those individuals who generously provided photographs and other information about the specific systems that we have used as examples. In some cases, these colleagues have also worked with us in developing some of these systems.

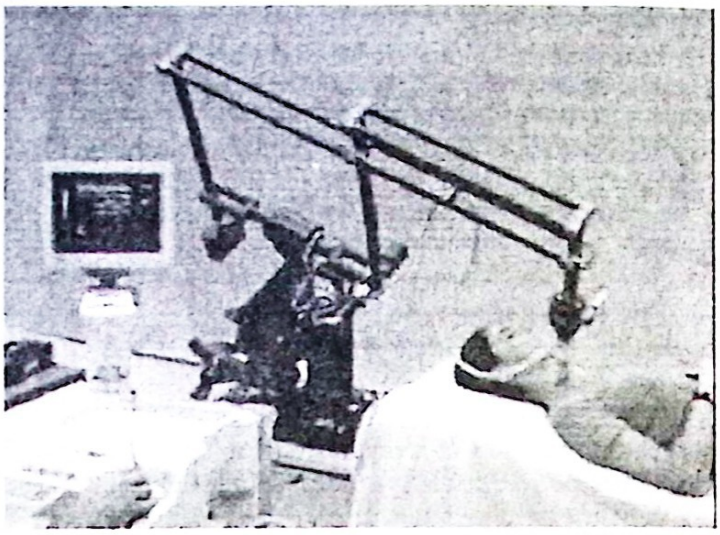

Figure 8: Ultrasound probe manipulation robot [70]

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Anatomical Shape-Based Averaging for Computer Atlas Construction and Craniofacial Anthropometry

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Abstract. We describe original methods for defining and obtaining robust, anatomical shape-based averages of features of the human head anatomy from a normal population. Our goals are computerized atlas construction with representative facial features and craniofacial anthropometry for specific populations. A new method for true-morphological averaging is presented, consisting of a suitable blend of shape-related information for N objects to obtain a progressive average. It is made robust by penalizing, in a morphological sense, the contributions of features less similar to the current average. Morphological error and similarity, as well as penalization, are based on the same paradigm as the morphological averaging. As a case of study, we tested the method for a shape-average of the external ear (the pinna) of 40 individuals.

1. Introduction.

Tele-assisted health services, distributed visualization of anatomical information in digital formats, image-guided surgery, and other activities where biomedical engineering, internet, medical imaging and computer sciences interact, rely more and more on reference information and representative items from large databases. These include: average models from a normal or specific population, anatomical and physiological atlases of human organs, baseline frames of reference, anatomical robust features (e.g. crest-lines of facial features), and phantoms or mannequins, either physical or virtual, for anthropomorphical studies, experimental assessment of different interactions between biological tissue and radiation, acoustic or electromagnetic fields, and simulation of endoscopic or surgical procedures, as well as for augmented-reality interventional medicine.

In particular, anatomical atlases and phantoms in digital formats are playing an increasingly important role in health sciences and biomedical research, as illustrated in Fig. 1. Computer models of anatomy and physiology are becoming more representative of a specific population of individuals, from organs to anthropomorphical features, and bear complex information providing references for identification of common features which are mapped to and from the atlas and then geometrically and photometrically registered. This allows inter-comparisons, and identification of abnormal conditions, for example. Model-based morphometry is thus a timely strategy for detection of disease-specific variants [1]. Multi-modality atlases allow also the assessment of pathology and treatment response, when combining several medical imaging techniques [10]. Since data to be analyzed is multidimensional and complex, atlases provide a reference, a "base truth", and a priori information used for anatomically-driven methods of analysis [2]. Models for

the simulation of surgery procedures and augmented reality are also derived from annotated models. Fig.1 summarizes these and other inter-relations.

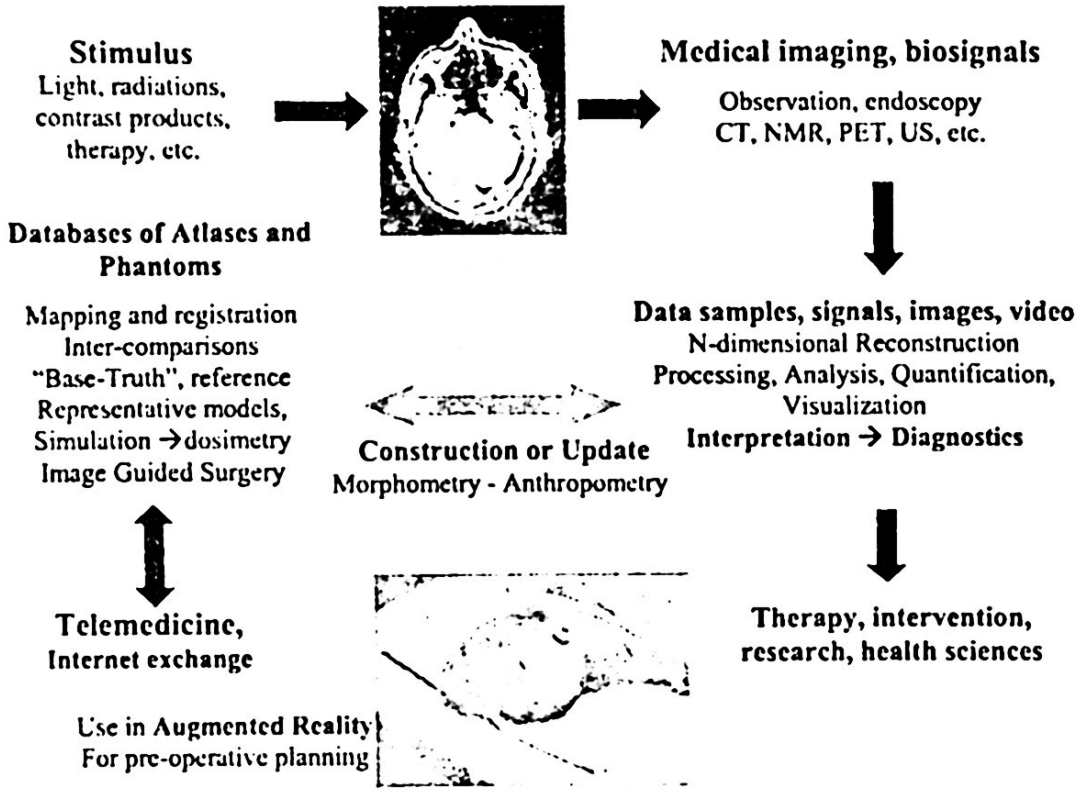

Fig. 1. The roles and context of atlases and phantoms in health sciences. The anatomical slice of the head is from the *Visible Human Project.*

Besides medicine, anatomical models are frequently used in industry, ergonomics and environmental studies. For instance, the shape alone of the head is considered in the study of power absorption and to design safe communication devices [1]. Concerning dosimetry of hand-held phones, the former motivation of the present study, the radio-frequency wave absorption by the human body not only depends on phone terminal positioning, but also depends on anatomical complex features, in particular at the ear and mouth regions. Homogeneous phantoms have been previously used [3], and accuracy improvements up to 2 mm precision resolution from MRI (*Magnetic Resonance Imaging*) scans have been made [4]. However, these studies use a single landmark-based average from army anthropometrical data of male subjects, not representative of the population of mobile phone users. Representative anthropomorphic phantoms from 3D laser-scan acquisitions allow both, simulation and experimental analysis of power absorption in a specific population.

Atlas construction must represent a set of individuals and its variability, by considering contributions from each individual according to some similarity with the true mean. Shape averages of organs and features have been built traditionally by standard arithmetic averaging of the coordinates of specific features, such as sets of landmarks and crest-lines [5]. These constitute averages in the *object domain.* A related approach to atlas construction is that of *statistical shape models* or *active shape models* (or ASM, see [20] and [21]), where statistical properties of several

objects are extracted from landmark information. The statistical or probabilistic and the fuzzy approaches give rise to "soft" models and atlases.

Our goal is to extract a representative instance of a specific (facial) feature from a large population, or from selected subsets. In this paper we describe a morphological, or *shape-based* averaging, generalizing the shape-based interpolation methods from two to N objects. It is an average in the *distance transform domain*, giving rise to "hard" models, where the average itself is an instance of the represented class of features. We also propose a robust rejection or penalization of outliers (rare variations), and test a simple framework for local penalization (local rare variations), in order to take into account only the most common sub-features. As a case of study, we present results for a shape average of the external ear, from a set of 40-individuals of the normal population.

The present work was originated by collaborations between the Image Dept. of the *Ecole Nationale Supérieure des Télécommunications* in Paris and the *Alcatel Corporate Research Center*, (Marcoussis laboratories, France). Details of the former project on automatic construction of head models are found in [3], [6] and [19].

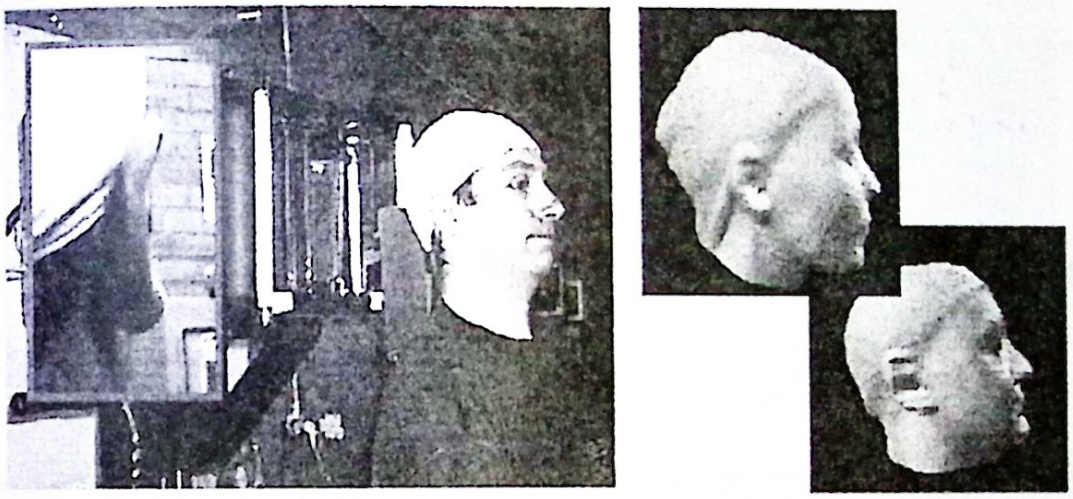

Fig. 2. Laser scan acquisitions of 40 people, with ear collapsed and free (inset). At *right*, renderings of the mesh models at 8mm resolution from cylindrical depth-range images.

2. Methods

2.1. Laser-scan acquisition protocol.

Laser-scan acquisitions were obtained from human heads and processed for the construction of anthropomorphical phantoms, required formerly for dosimetry studies of hand-held mobile phones. Fig. 2 shows the acquisition setup, with a 3D laser scanner from *Cyberware* [7], which rotates around the head, producing distance information of the 3D relief. In total, 40 subjects were scanned, with 12 women in the final sample. Raw data was converted to cylindrical range images at 480×580×5-byte (floating point) resolution, and several image processing techniques were applied for 3D-model construction [19], in order to filter out artifacts and noise, preserving accuracy, and to locate morphological features in *image space* and then in *object*

space [8]. A triangulated surface was obtained for rendering, and for CAD, in order to build physical phantoms. Interactive 3D visualization of mesh models is based on the VRML (*Virtual Reality Modeling Language*) format, and was used for browsing the models in a tele-collaboration framework across Internet. A voxelized version was also produced (Fig. 3-a, b) for processing and for finite-element simulations.

In Fig. 3 a-b, two voxel-volume heads are visualized, with discrete labels in color locating ear, no-ear, and interpolated intruding and extruding tissue. Such volumes were prepared for simulation of radiofrequency-field interactions with the head tissue. Small colored isolated voxels arise from the randomized diagonal swapping of the Eulerian triangulation before voxelization, and they are of no importance.

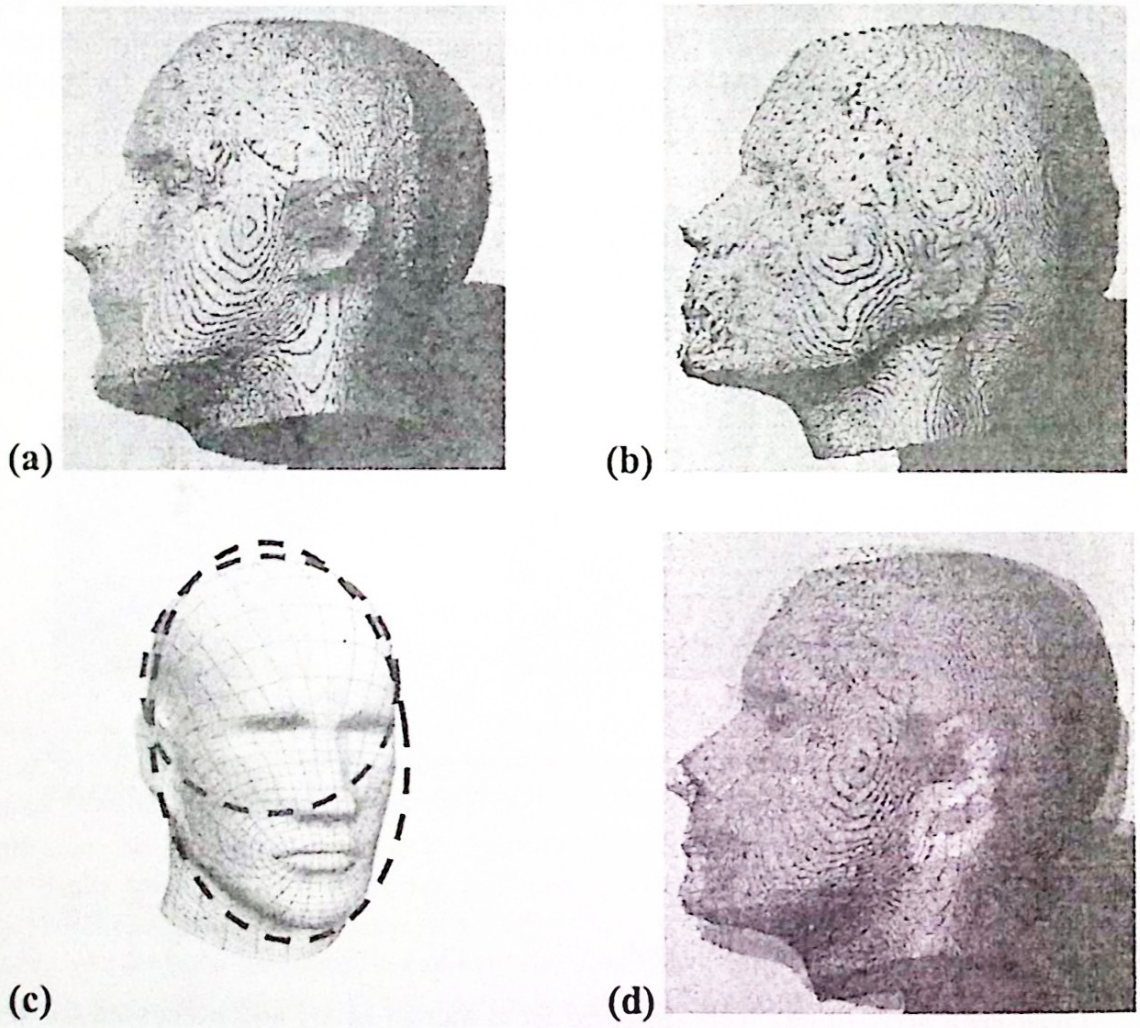

Fig. 3. Even if two heads (a) and (b) from the database are geometrically registered and scaled by (c) robust principal-axis alignment (ellipsoidal, first-order model, in red; zero-order in blue), a 3D superposition of two "aligned" heads (d) shows features at very different positions (order zero provides the best alignement of the auricular-temporal region).

The ear region was then isolated and replaced by a *bilinearly-blended Coons patch surface* that interpolates the skull, using the range-image information around the ear, synthesizing the Coons spline by the tensor product of orthogonal profiles. A baseline implicit surface was thus defined (see also Fig. 3-a,b), useful for measuring

features of human heads; in particular, an average thickness of the ear was estimated on 40 individuals; further details are found in [9]. Head models "with" or "without" ears were built for assessing dosimetry and anthropometry problems. The range-image representation was also convenient for other manipulations and measurements, since 3D information is displayed in the *Mercator cylindrical projection* as a gray-level image. This projection also simplified the interpolation of the auricular-temporal region, and the 3D geometric registration, as explained next.

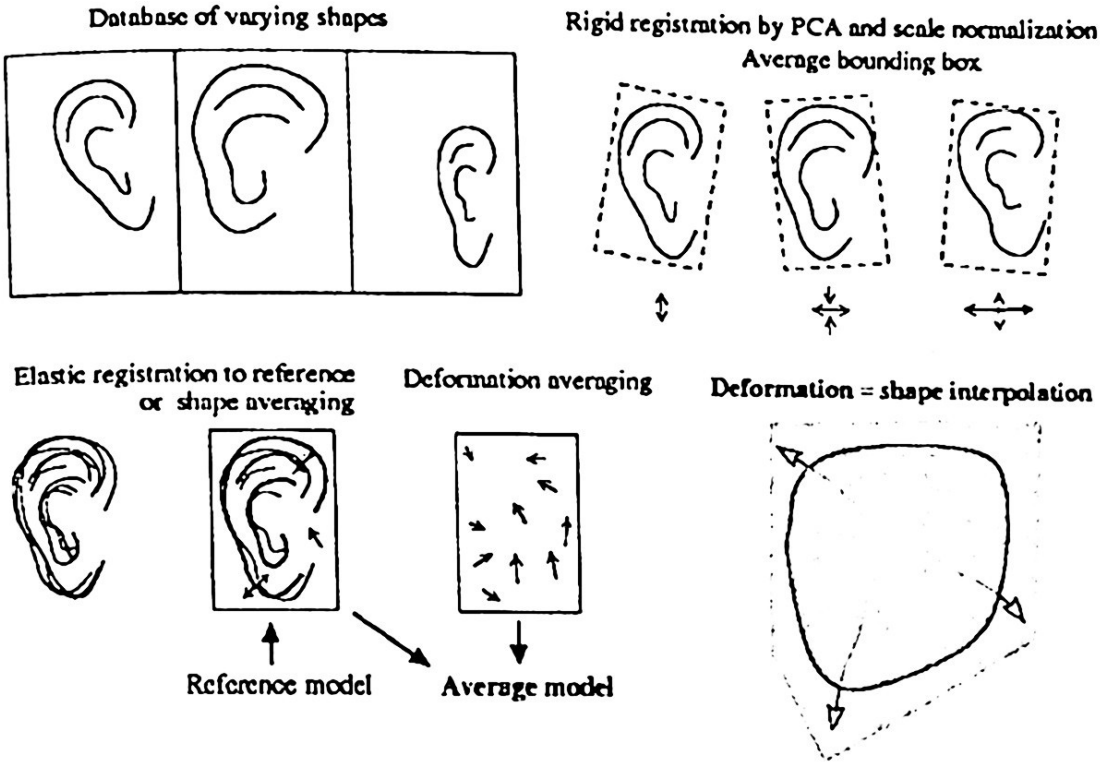

Fig. 4. Simplified process for the construction of average models. The concept of morphological average comes from that of morphological interpolation between two similar shapes (*bottom right*), where the transformation has to deal with the correspondence problem.

2.2. Feature-Based Registration.

Morphological tasks such as comparisons and averaging require first a geometrical correspondence of datasets in a common frame of reference. Non-linear registration of matching features is a challenge for atlas construction, in particular for the highly varying shape of human anatomy [10], and the external ears are a typical example. In a first approach we used a global alignment of principal axes for the bounding box of the auricular-temporal region. Note that a global alignment of the full heads is not useful, as illustrated in Fig. 3, where the ears are far from superposing. A similar problem arises when global alignment is confined to the bounding box of the ears. A better approach was to extract robust features of the ears, such as the external crest-lines, available from the depth-range images. In the case of brain structures, the atlas construction process has been adapted to multi-modal imaging [5], and a similar framework is illustrated in Fig. 4, where we have integrated

our approach considering shape-based interpolation (bottom right) as a deformation. Note that an affine registration is required, since ears vary in size and shape.

We used the *Iterated Closest Point* (ICP) algorithm [11], which is a general purpose, shape-based registration. The steps for geometrical registration comprise:

- External ear (pinna) contour (crest lines) extraction, from the depth-range images of each head before mesh construction.
- Bounding-box extraction in 3D for each contour.
- Principal Component Analysis to obtain the 3D-inertia axes.
- Principal axes alignment (preliminary step for ICP alignment).
- Affine registration transform of contours by the ICP algorithm.
- Average transformation.
- Average ROI (bounding-box); average scale calculation.
- Scale normalization of all heads.
- Hi-resolution mesh (~2mm) and mesh transformation.
- Voxelization of ROIs. The registered set is ready for averaging.

The same procedure was applied to the implicit surfaces underlying the pinna. Fig. 5 shows the feature-based registration, using the crest-lines of the ear borders, and their bounding boxes. Cylindrical coordinates of data from the laser-scanner acquisitions allow to work with 3D surfaces data as 2D depth-range images, thus a "2D" bounding box is shown, but the process was done in 3D, before mesh bulding and voxelization. Matching of local features is only approximate, and there may be several deformation paths, or, equivalently, several interpolation paths, as illustrated by the slightly curved arrows of the morphing process of Fig. 4, bottom right. Energy-minimization criteria have been proposed to obtain an optimal interpolation [12], but its computer complexity is too high even for low resolution data, and there is no evidence for deformation-energy processes to explain inter-individual variations.

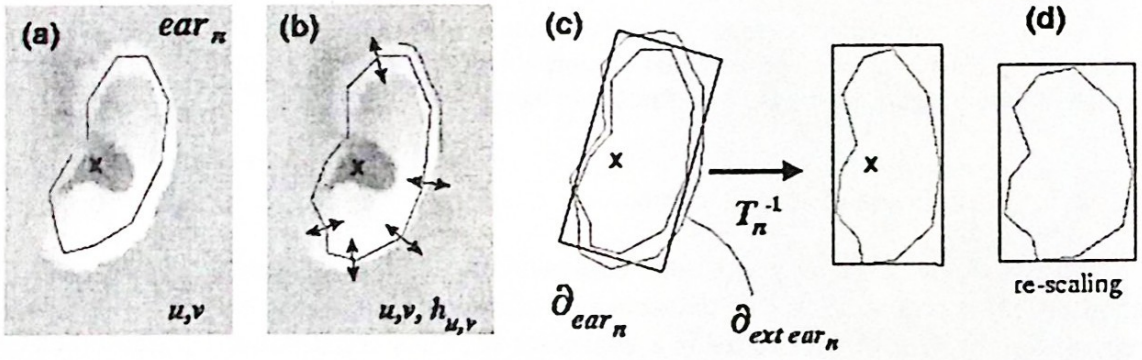

Fig. 5. Local, inter-individual registration of the external ear region was based on affine registration of robust features: the crest-lines of the ear borders from the range-images (a,b). Rotation (c) and homogeneous scaling on the 3D bounding box (the figure shows a 2D projection) was done using the average bounding box as reference (d).

The resulting alignment, for a sample of 5 ear borders, is illustrated in Fig. 6. In spite of original registration of the heads during acquisitions, the ear shapes have quite different positions and orientations, besides shape and size variation. An average bounding box provided a frame of reference and a common scale for all ears.

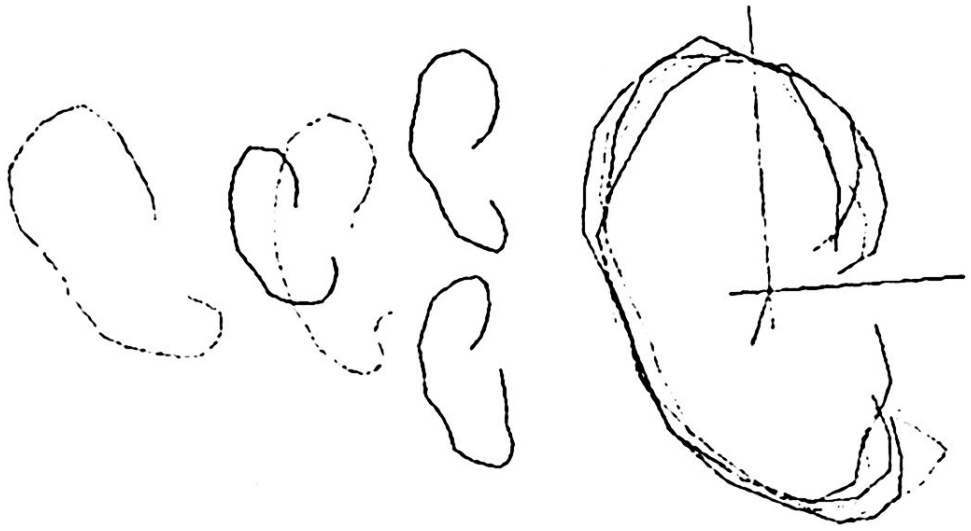

Fig. 6. Feature-based registration. (*Left*) 3D-reference contours (border of the ear) before affine registration. (*Right*) Superposed contours after homogeneous scaling and registration by *Principal Component Analysis*, i.e. alignment of each set of 3D axes of inertia.

2.3. From morphological interpolation to shape-averaging.

Morphological interpolation techniques have been introduced in several fields, from industrial design, to medical imaging, with the common goal of effectively interpolating shape profiles, and binary shapes between consecutive image slices, as opposing to signal interpolation in a point-to-point basis on gray-level images. Specific techniques are described in [13], [14], [15]. The concepts of metamorphosis and morphing, are special cases, when interpolating very different, unrelated shapes, with arbitrary correspondence criteria [16], [23]. Slice-image, linear interpolation between two similar shapes is usually done as follows.

Let A, B be two discrete objects and let $\mathbf{D}_A$ y $\mathbf{D}_B$ their discrete, signed distance fields (also known as distance transforms), then the linear *blending* $\mathbf{D}_\alpha = (1-\alpha)\,\mathbf{D}_A + \alpha\,\mathbf{D}_B$ provides a simple way to interpolate an "intermediary" object $\mathbf{D}_\alpha$ between both A, B (these interpolation process is popularly known as "morphing"). The corresponding shape is extracted from iso-surface at a threshold distance zero. The last is also known as a zero-level set. The exact average shape corresponds to $\alpha=1/2$. Since it is a linear operation, a third shape C allows conceptualizing a triangle in "shape space" (or more properly, the distance-transform domain) whose vertices are A, B and C, and the central interpolated shape is a shape-based average. Thus, we introduce a N-object average, first listing the following:

Definitions

$\mathcal{V}$ Digital scene, usually a N×M×L volume. The volume $\mathcal{V}$ may be also a *scalar field*, it is, at point (x,y,z), the quantity $d = \mathcal{V}(x,y,z)$ is a scalar.

V Discrete object in $\mathcal{V}$ (e.g., digital information of an anatomical structure, represented by an array of scalar or vector values, or a mesh structure).

∂V Boundary of the object V (its discrete surface). It depends on segmentation or selection criterion (e.g. external surface of an organ, bone, arteries, etc.).

$\mathbf{D}(\partial V)$ Signed distance field (a discrete volume with scalar values) associated to boundary ∂V. Note that $\mathbf{D}(\partial V)$ is a scalar field. It is also called the (Euclidean) *Distance Transform*. For simplicity we use the notation $\mathbf{D}_V$.

$L_{d=d0}(\mathcal{V})$ Level-set (iso-surface at $d=d_0$) of a scalar field. Note that under certain conditions, at distance $d=0$ it is possible to define $L_{d=0}$ as an inverse transform: $\partial V = L_{d=0}(\mathbf{D}(\partial V))$.

$< x_i >$ Conventional average (expected value) of N simple data x_i.

$\overline{\partial V}$ or $\ll V_i \gg$ (Any) morphological average of N objects V_i, to be defined later.

$\ll V_i \gg_R$ Robust morphological average. This shape is the basis for a representative model or *atlas*, when labels and attribute information are incorporated.

With the latter notation, we introduce the Euclidean (in the case of Euclidean metric), and the Chamfer (in the case of discrete metric for chamfer-distance transforms) *morphological average* based on the signed distance field associated to the boundaries ∂V_i of each object V_i:

$$\overline{\partial V} = \ll V_i \gg = L_{d=0} \left\{ \sum_{i=1}^{N} \mathbf{D}(\partial V_i) \right\} \qquad \text{eq. (1)}$$

The zero-level set is the external iso-surface (or boundary) of the average object. Both notations correspond to two interpretations of the result, as a boundary $\overline{\partial V}$ of an object V and as a morphological average among several instances V_i.

The averaging can be made "robust" in a statistical sense, when each shape-term of the sum is penalized according to its similarity to the current average, and then recalculating the latter (see Fig. 7). Let $\{ w_i \}$ the normalized set of weights; the starting condition is an homogeneous contribution such that $\Sigma_N w_i = 1$, and we define a *robust (Euclidean or Chamfer) morphological average*:

$$\ll V_i \gg_R = L_{d=0} \left\{ \sum_{i=1}^{N} w_i \mathbf{D}(\partial V_i) \right\} \qquad \text{eq. (2)}$$

An iterative method allows to find an optimal set $\{ w_i \}$ from an error measure to be minimized when comparing ∂V_i with $\ll V_i \gg_R$. The error space is for the moment assumed to be convex (no local minima), but a better analysis needs to be done.

A mechanism to compare 3D objects is to use the distance fields of each shape, in order to define a "morphological error", which can be based on a squared difference, voxel-to-voxel and for each scalar field. For all voxel values

$u(x,y,z) \in \mathbf{D}(\partial V_i)$ and its corresponding value $v(x,y,z) \in \left\{ \sum_{i=1}^{N} w_i \mathbf{D}(\partial V_i) \right\}$,

the volume set $Err^2(V_i)$ is formed with the voxel values:

$$err^2(x,y,z) = \left[v(x,y,z) - u(x,y,z)\right]^2 \qquad \text{eq. (3)}$$

Note that Err^2 (V_i) is a scalar scene. Integrating in all (x,y,z) we obtain a global measure of error, permitting evaluation of a weight for ∂V_i when averaging at iteration n+1. Note that local integration on any specific region, allows evaluating the contribution to global error for that region. Thus, weights w_i may be variable, either point to point, locally, or even by very specific ROI's (a facial feature, for example).

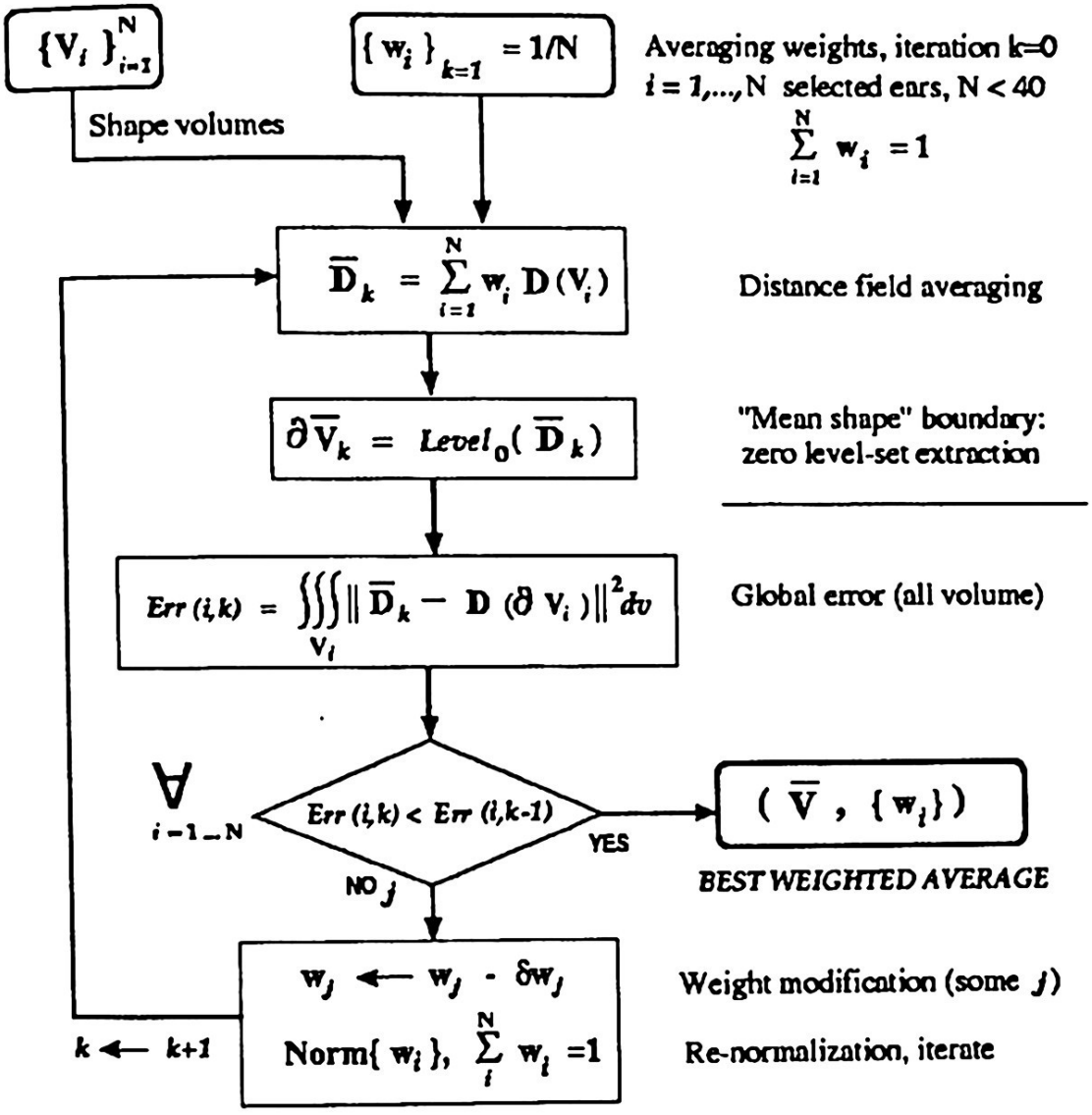

Fig. 7. The robust shape-based averaging algorithm for a set of N shapes $\{V_i\}$. The set of weights $\{w_i\}$ is shift-invariant, but may also be a function of position (x,y,z), or assigned locally to each sub-feature of V_i.

An incrementing algorithm, modifying one w_i at a time, was devised to avoid re-calculating the distance-field average again, by subtracting the contribution of ∂V_i at iteration k-1 and updating it with the new value for w_i. A similar approach works for new shapes to be included in the average, which is the essence of a population atlas which is more representative at each contribution.

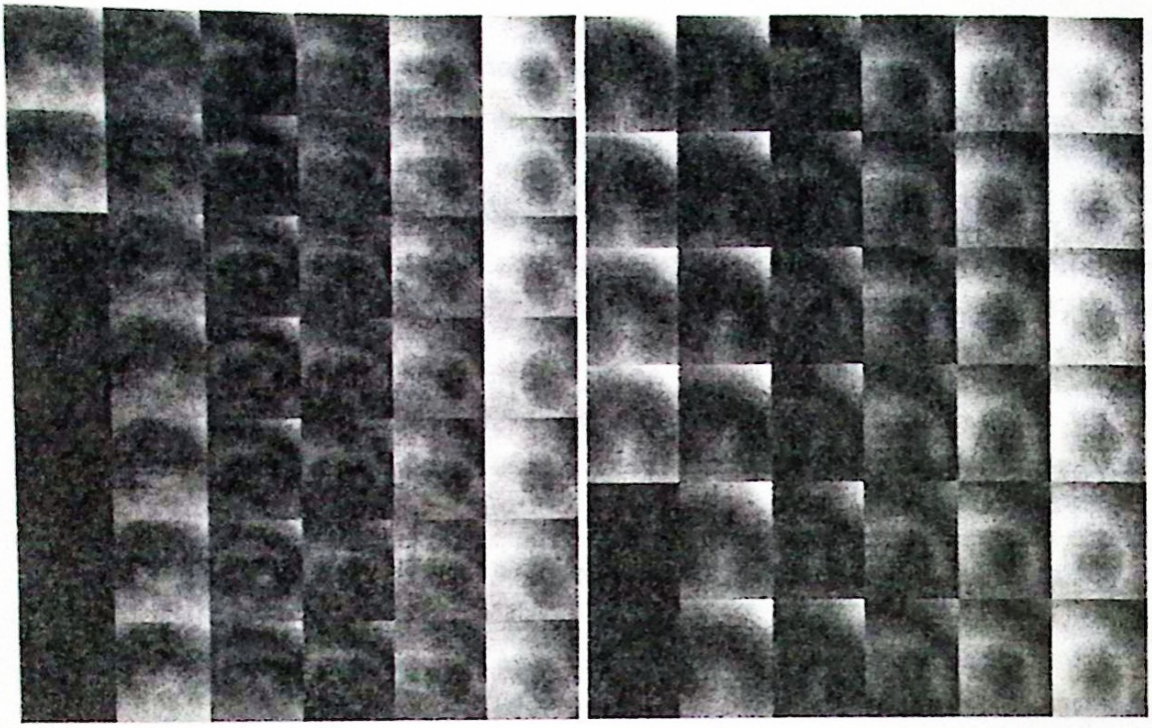

Fig. 8. (*Left*) Unsigned 3D distance field of the boundary of one human ear. (*Right*) Idem, distance field averaged over 40 individuals.

Figure 9 (right), shows a 3D rendering of the resulting average shape, extracting a triangular mesh from the voxel-representation results, and its interpolated, implicit, base surface (middle surface, in sky blue), once integrated to a generic phantom.

3. Results and Discussion

Figure 8-a shows a few Z-slices of the unsigned 3D-distance field of the surface boundary of one human ear (binary information). The "unsigned" version shown, i.e. |d|, is a display enhancement by look-up tables, to make visible the cross sections of the 3D boundary of the ear and to better display the field gradient. Fig. 8-b shows also slices (not the same Z-levels that Fig, 6-a) of the average distance field within 2 mm of global error over 40 individuals. The level set at Z=0 (gray level black in the figures) corresponds to the boundary of the original shape *i* and the averaged shape. Note that averaging on 40 shapes produces a smoothed shape. There remains the question of validating the average as a feasible human ear, and the method could be refined by constraining the error minimization while respecting some ear-ness criterion. An answer to the question "to what extend the shape-based average is a valid human ear" lies on the size of local mismatches: the average is an interpolation among real ear features, provided that their extrema correspond one-to-one. A correspondence mismatch implies an invalid local interpolation of at most the size of that mismatch. Non-rigid registration may help to improve correspondence matching.

To reproduce the situation of users of mobile-phones, the acquisitions comprised a version with the ear collapsed against the skull. The thickness of the corresponding averaged ear, measured by methods reported in [9] was about 6.2 ± 2.5 mm, and

agrees well with the measure of this thickness in the *Standard Anthropomorphic Model* [17], obtained by different methods.

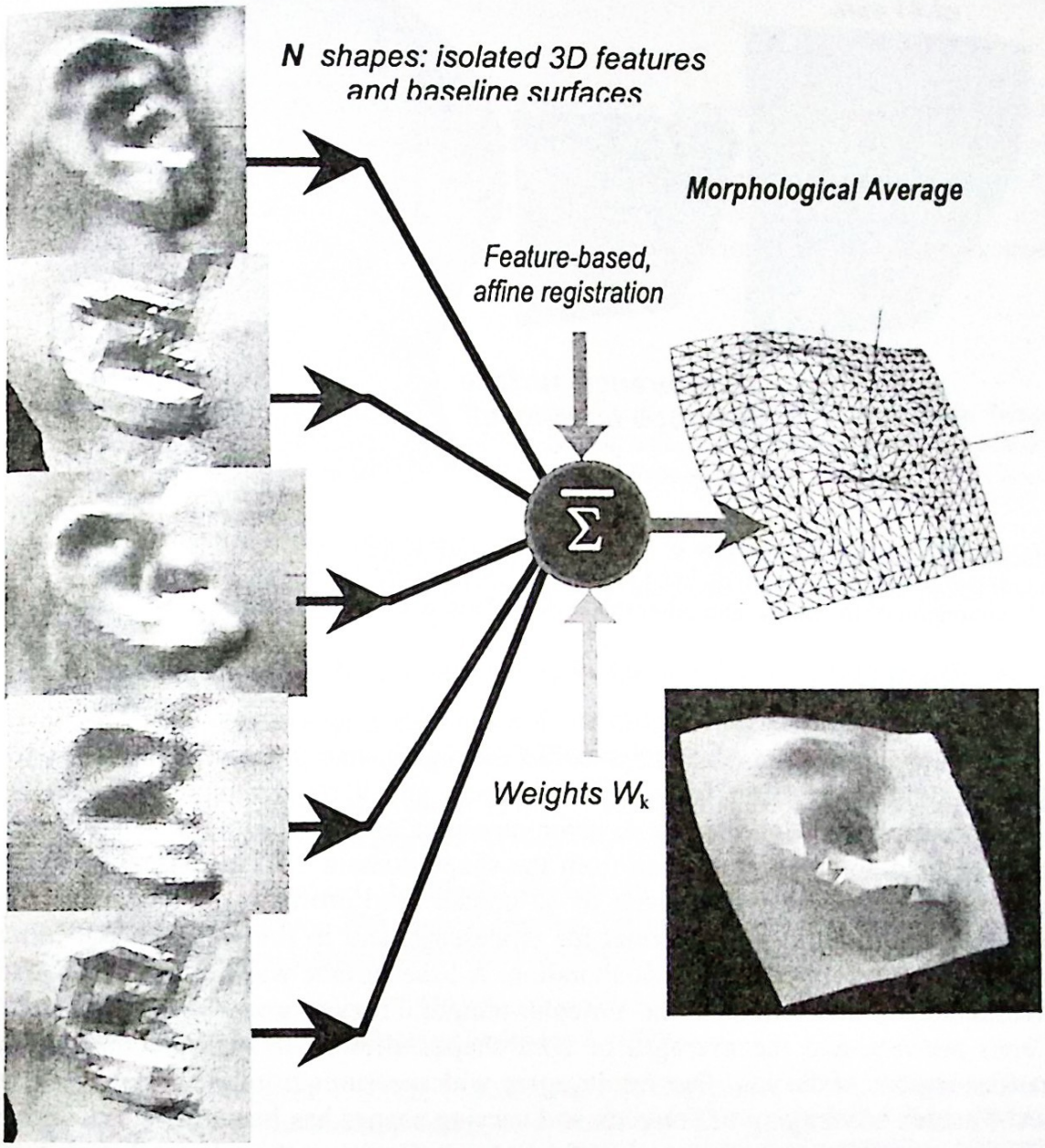

Fig. 9. (*Right*) Elements for the construction of an anatomical, robust, morphological-average of the ear from 40 individuals. Features are the border lines of Fig. 6. (*Left*) A 3D rendering of the resulting average shape (triangular-mesh representation).

The present approach also permitted averaging the implicit surface that interpolates the skull, described in [9]. Thus, a morphological-average of the head "without ears" can be obtained, too, and Fig. 10 illustrates the construction of morphological averages of the ear and its corresponding average implicit-base surface, integrated to a generic head phantom (virtual as well as physical) for dosimetry studies.

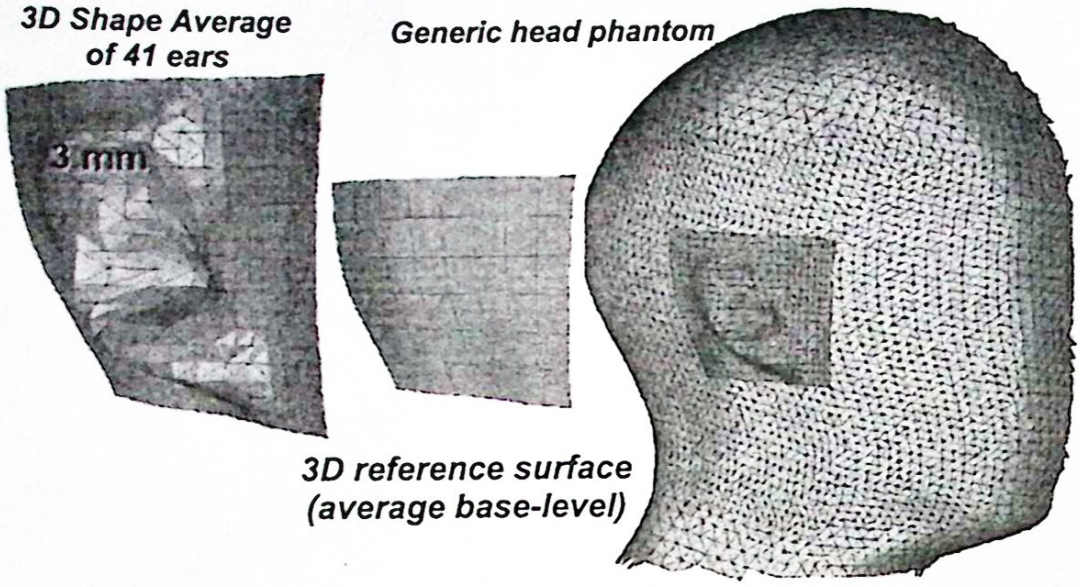

Fig. 10. Morphological averages of the ear and its corresponding average implicit-base surface, integrated both to a generic head phantom. The measure "*3mm*" corresponds only to a subregion of the pinna, and other thickness values, at different regions, were obtained.

4. Conclusions.

An innovative method of shape-based averaging was presented. It blends the distance-field information from several shapes, and a robust implementation was obtained, applying similar ideas to error measures and similarity, calculated in the distance-field domain, rather than from the shape domain. To test our methods, an average of the ear from a database of 40 human head profiles was obtained. The database was build in voxel format for processing, and in the web-oriented format VRML, for browsing and tele-collaboration. A base surface was defined an obtained from boundary information at the auricular-temporal region, using *bilinearly-blended Coons patches*, and the averages of both shapes allowed to measure thickness at various regions of the ear. Our results agree with measures from the widely accepted SAM model. Averaging of complex and varying shapes has been difficult without a reliable geometric registration, and the implicit Coons surface has alleviated this problem, providing also a baseline for error quantification during registration. A feature-based approach, using the crest-lines of the external ear, was also used for a more robust registration, before averaging in the distance field domain. Registration may be based also on distance fields, a procedure known as "chamfer matching", and a combination with line feature-based registration is possible by modulating distance fields. Future work comprises these enhancements, as well as averaging methods including not only weighted distance fields, but also the fields of non-rigid deformations.

The construction of models of anatomical features from a specific population is becoming a key-step towards digital atlases which integrate annotated information, morphometry and even physiology (e.g. functional imaging). Computer phantoms of facial features from these models will be useful in simulation of craniofacial

reconstruction, anthropometry and to build virtual and physical prostheses, which can be made highly customized, at least to a local population.

Acknowledgments

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Computer Assisted Prostate Surgery Training

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Abstract. In this work is described the development of a computer simulator for training on Transurethral Resection of the Prostate (TURP) based on a computer model of the prostate gland which is able to simulate, in real time, deformations and resections of tissue. The model is constructed as a 3D mesh with physical properties such as viscosity and elasticity. We describe the main characteristics of the prostate model and its performance. The prostate model can also be used in the development of a Computer Assisted Surgery system designed to assist the surgeon during a real TURP procedure. The system will provide 3D views of the shape of the prostate of the patient, and the position of the surgical instrument during the operation. The development of new computer graphics models which are able to simulate, in real time, the mechanical behavior of an organ during a surgical procedure, can improve significantly the training and execution of other minimally invasive surgical procedures such as laparoscopic gall bladder surgery.

1 Introduction

Computer assisted surgery (CAS) and medical robotics systems share the common objective of providing the surgeon with different levels of automatic assistance during planning and execution of a surgical procedure. This is achieved through the integration of: Measurements taken on medical images; Three dimensional (3D) tracking or positioning systems; Computer vision and graphics techniques; and Robotics techniques. Computer assisted and robotic surgery systems differ in the assistance provided during execution. A computer assisted system provides image or model based guidance to the surgeon inside the operating site using a non-contact tracking device such as an optical tracker, while the whole procedure is performed manually by the surgeon [1]. A robotic surgery system provides guidance to the surgeon using a mechanism which can be passive or motorized in which case some or all of the surgical actions are performed by the robot [2][3].

Medical robotics surgery systems can be classified according to the level of automatic assistance provided to the surgeon. Passive surgery assistant robots provide passive guidance to a surgeon who performs all the surgical operations manually. Active assistant robots use motorized mechanisms to perform surgical operations under the supervision of the surgeon. Synergetic assistant robots use motorized mechanisms to produce active constraints which limit the movements of the surgeon

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to safe regions inside the operating site [4]. In Fig. 1 is shown the active assistant robot for Transurethral Resection of the Prostate (TURP) [5].

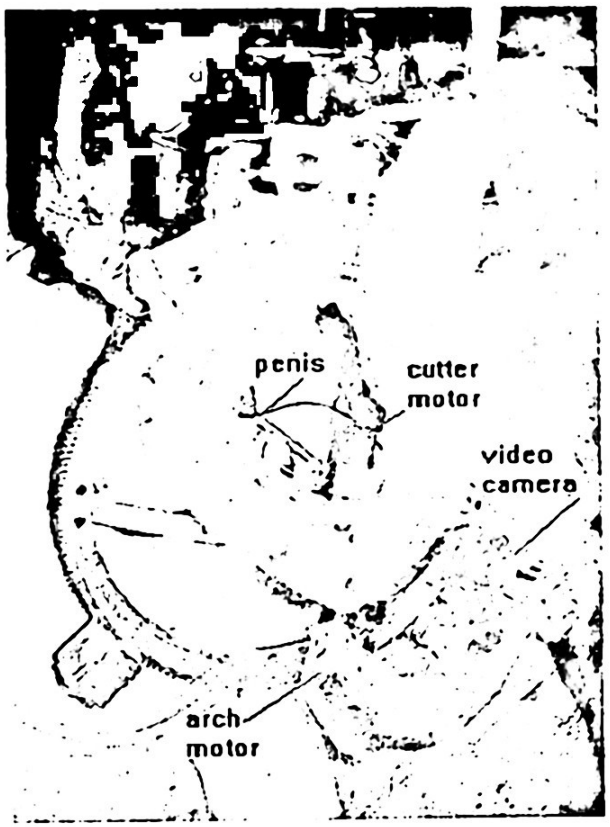

Fig. 1. Assistant robot for prostate surgery

Among CAS systems we have computer simulators for surgeon training and assistance. A computer simulator provides a realistic environment for intensive training of the skills needed for a given surgical procedure. During the execution of a real procedure, the computer model of the organ of the patient can also be used to monitor the progress of the operation. Computer simulators for surgery will significantly benefit from the development of computer models of human organs able to be deformed and resected. In the following sections we present a deformable model of the prostate for TURP surgery simulation.

2 Transurethral Resection of the Prostate

The prostate is a chestnut size gland, located just below the bladder, surrounding the urinary duct of human males. As part of the ageing process the prostate grows and, in some cases, obstructs the urinary flow. This is a common illness in men more than 50 years old. Enlargement of the prostate is treated by surgically removing the obstructing tissue in order to reestablish the free flow of urine. In Fig. 2 is shown the basic anatomy of the prostate.

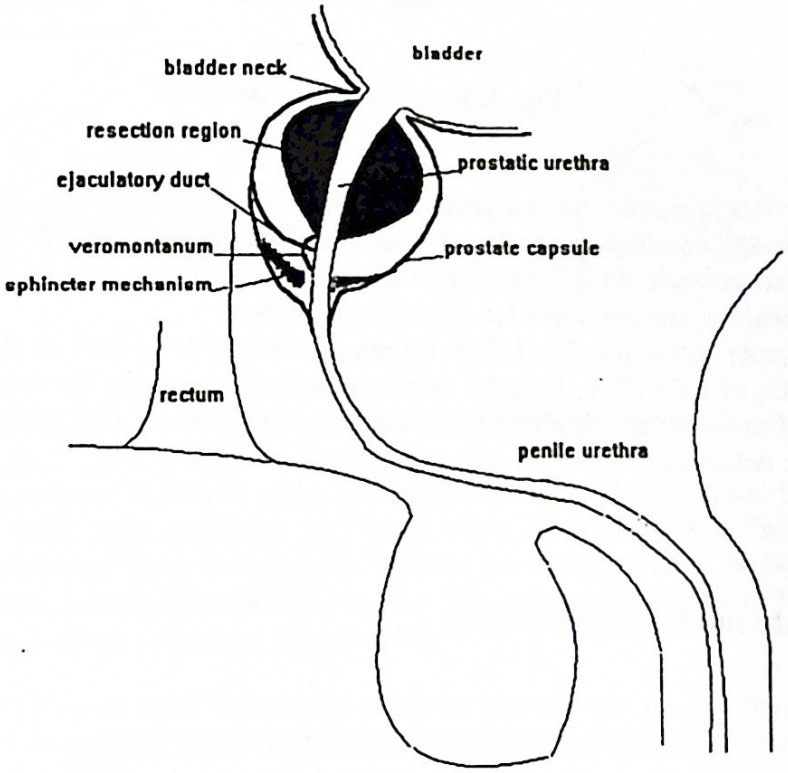

Fig. 2. Anatomy of the prostate

The standard procedure to treat an enlarged prostate gland is the transurethral resection of the prostate in which a surgical instrument called resectoscope (Fig. 3) is inserted through the urethra of the patient. The resectoscope carries in its interior a telescope and a resecting loop that enables the surgeon to remove small chips of prostate tissue.

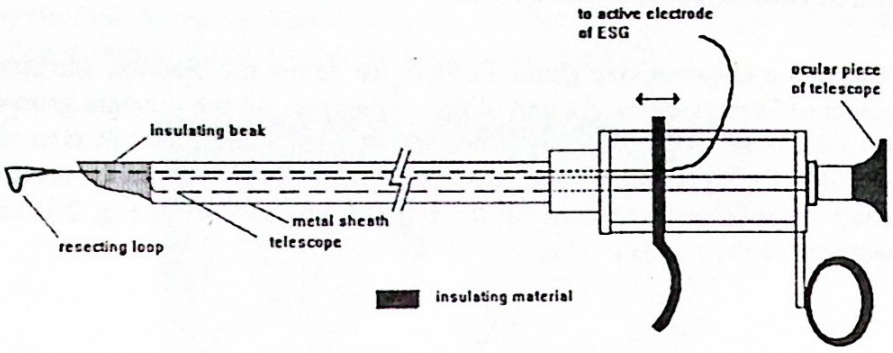

Fig. 3. Resectosocope for TURP

During the operation the surgeon orientates himself inside the prostate of the patient through continuous checks of anatomical landmarks like the *verumontanum* and the bladder neck. TURP training is an slow and difficult process since there are very few practice opportunities for the urology resident.

A computer simulator for TURP training is being developed at the Image and Vision Lab., of CCADET, UNAM, with the aim of improving the training process, the core of the simulator is a computer model of the prostate able to simulate in real time tissue deformations and resections produced during a TURP.

3 Prostate model construction

In our current version, the prostate model is constructed from a set of contours drawn by an expert on the corresponding set of transurethral ultrasound images of the prostate of the patient. An example of annotated ultrasound images is shown in Fig. 4. An automatic alternative for prostate recognition in ultrasound images is being developed at the Image and Vision Lab. [6].

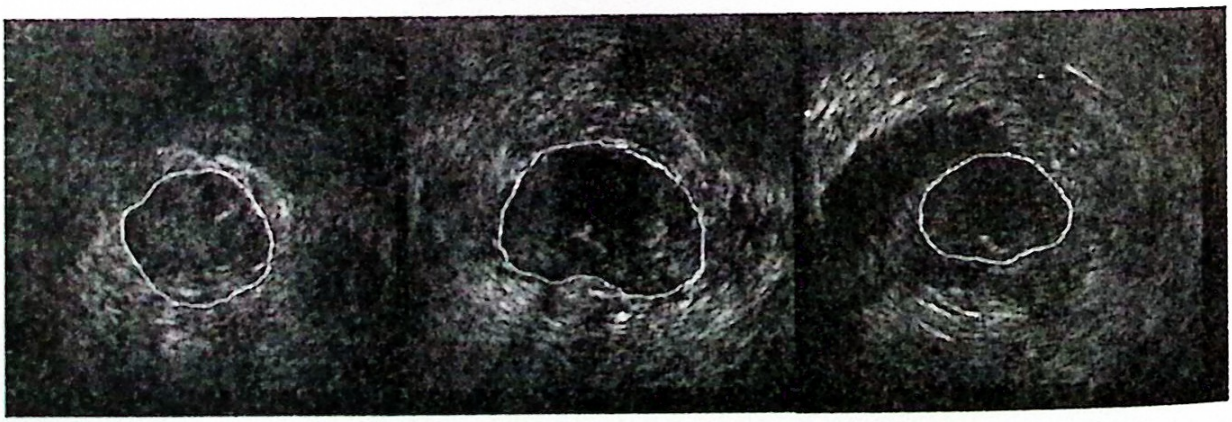

Fig. 4. Annotated ultrasound images of the prostate

Five transversal images were used to construct our current model, each of the prostate contours was radially sampled. New contours were calculated using cubic spline interpolation, a 3D volume of the prostate was build from the whole set (Fig. 5a). Both the angle α in the radial sampling and the number c of points in the cubic spline, interpolation, shown in Fig. 5b, can be adjusted in order to get a 3D mesh with enough visual realism and acceptable time response.

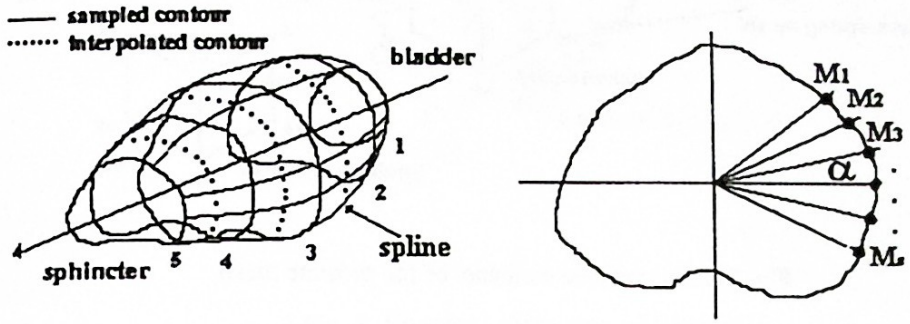

Fig. 5. a) 3D volume of the prostate; b) Contour sampling.

To model the prostate as a solid body, and to propagate the deformations through its structure, we built, from the shape previously obtained, a volumetric finite element mesh. Several layers from the prostate capsule (external surface) to the prostate urethra (internal surface) were interpolated for this purpose, as shown in Fig. 6. The volumetric mesh of the prostate is shown in Fig. 7.

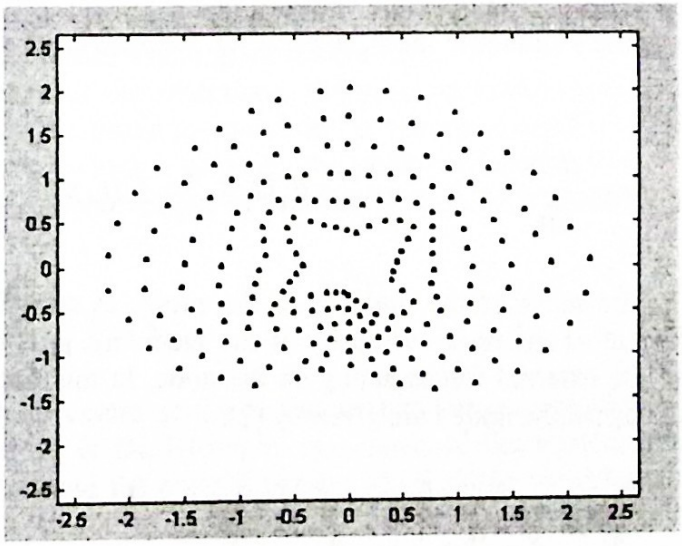

Fig. 6. Inner mesh nodes.

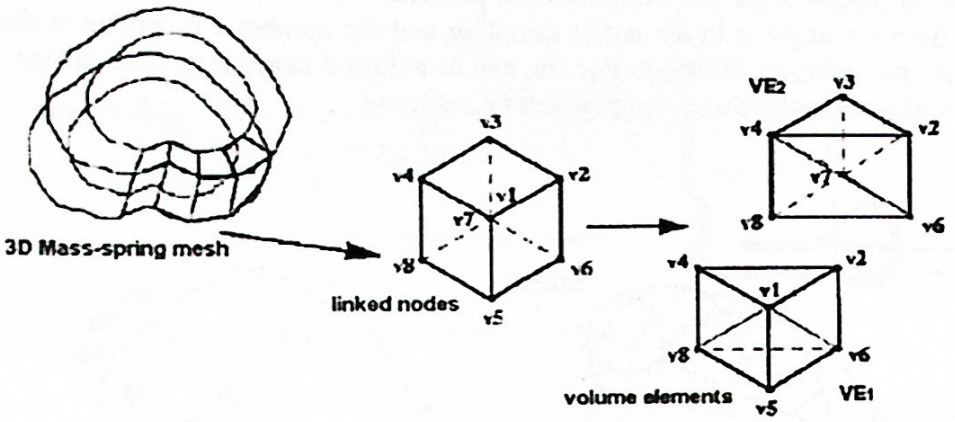

Fig. 7. Final volume elements of the prostate mesh

3.1 Adding physical properties to the prostate mesh

The prostate physical behavior is modeled as a deformable body with physical characteristics like mass, stiffness and damping coefficients. These physical characteristics were adapted to the volumetric 3D mesh constructed before, to produce a viscoelastic 3D mesh. This was done using the spring-mass method [7] (see Fig. 8), which allows us to perform real time deformations. Every node in the mesh represents a mass point that moves in a viscous medium, and is interconnected with its neighbors by springs. The dynamic behavior of the system, formed by the spring-mass elements in the volumetric mesh, is based on the *Lagrange* equation of motion (1).

$$m_i \frac{d^2 \mathbf{x}_i}{dt^2} + \gamma_i \frac{d\ \mathbf{x}_i}{dt} + \mathbf{g}_i(t, \mathbf{x}_i) = \mathbf{f}_i(t, \mathbf{x}_i) \qquad (1)$$

Where m_i is the mass of the node N_i in the mesh, at coordinates $\mathbf{x}_i$; γ_i is the damping coefficient of the node (viscosity of the medium); $\mathbf{g}_i$ is the internal elastic force and $\mathbf{f}_i$ are the external forces acting on the node. In this approach the internal elastic forces acting on the node i are given by (2).

$$g_i = \sum_{j \in N(i)} \mu_{i,j} \frac{\left(\left\|x_i - x_j\right\| - l^0_{i,j}\right)\left(x_i - x_j\right)}{\left\|x_i - x_j\right\|} \qquad (2)$$

Where $\mu_{i,j}$ is the stiffness coefficient of spring connecting node N_i and N_j for all the neighbors in $N(i)$ and $l^0_{i,j}$ is the spring length at rest position. In this manner, the

deformations occurs as a result of the elastic inner energy change, produced by the spring elongation.

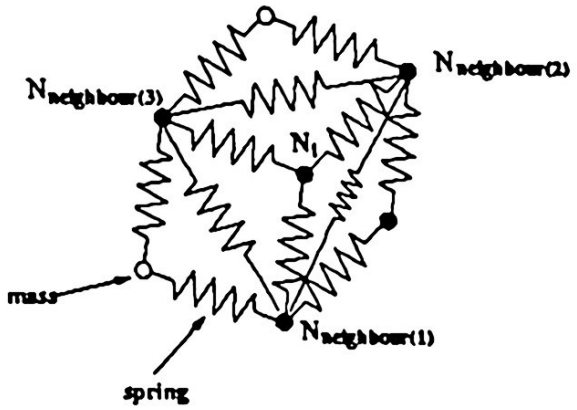

Fig. 8. Physical elements of the mesh

3.2. Tissue Resections and Prostate Deformation

If a collision between the prostate and the resectoscope body is detected, the contact vertex in the mesh is calculated. Then, the geometrical elements (pentahedrons and triangles) and mechanical elements (springs) that surround the vertex are removed from the mesh. Finally the contact vertex is also removed from the mesh. In order to visualize the inner tissue exposed after the resection (after removing the adjacent elements of the contact vertex), the elements corresponding to the tissue exposed are added to the surface mesh, which is the visible layer.

As a consequence of the resections, the prostate model must deform due to the pressure exerted by the tissue surrounding the cutting zone. This pressure acts in (1) as an external force $\mathbf{f}_i$, which is given by the volume variation in the cutting zone. The pressure has been modeled locally in the cutting zone, in a similar way as a hydraulic system (3).

$$\mathbf{p}_i = k_i \mathbf{dV}_i \tag{3}$$

Where $\mathbf{p}_i$ is the pressure acting in the contact vertex, due to the removal of the surrounding tissue; k_i is the hydraulic resistance of the contact vertex; $\mathbf{dV}_i$ is the volume variation around the contact vertex. The volume variation $\mathbf{dV}_i$ is defined by (4).

$$dV_i = c_i \sum_{j \in VA(N_i)} \frac{V_j^c}{V_j^0} \tag{4}$$

Where V_j^c is the volume of the pentahedron v_j adjacent to the contact vertex N_i ($\forall$ $v_j \in VA$, where VA is the set of pentahedrons adjacent to the contact vertex); V_j^o is the initial volume of all the pentahedrons adjacent to the contact vertex; c_i are the coordinates of the cutting zone center.

4 Results

The model described was implemented in C using the OpenGL libraries for rendering, on a SUN BLADE 2000 workstation (with one processor at 1 Ghz), without specialized graphics hardware. The slides on Fig. 9 show a simulated resection of the prostate model. The figure presents a prostate with an urethra, almost completely obstructed by the tissue that has grown in excess (top left slide) The slides also show the removing process of the adenoma. It can be observed the cavity produced after several tissue resections from the obstructed urethra, and the progressive collapse of the inner tissue.

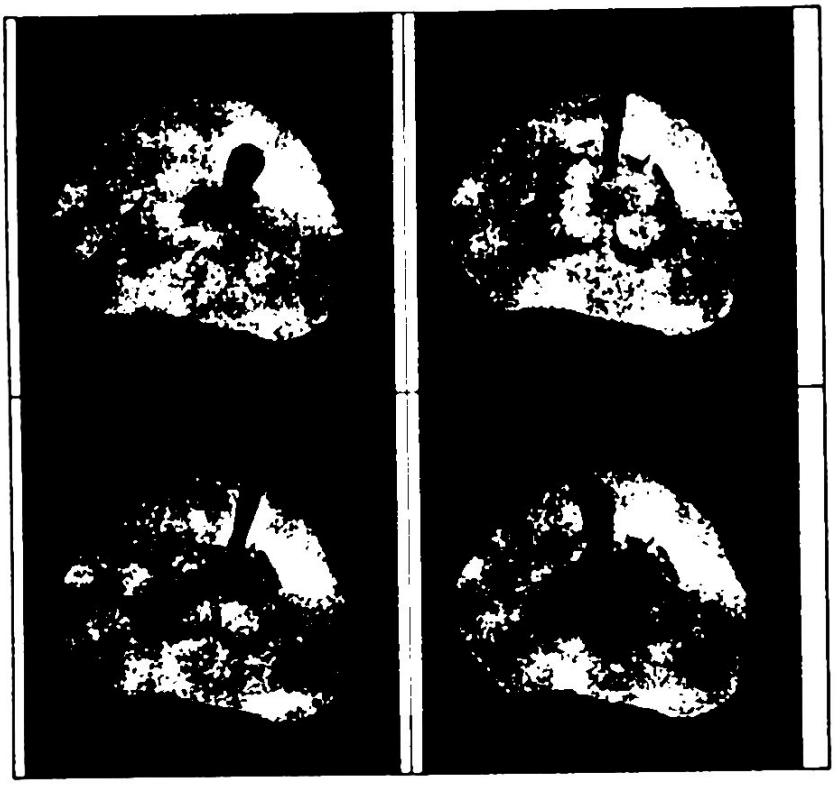

Fig. 8. Resection and deformation of a prostate model with 10800 nodes in its mesh.

5 Conclusion

This paper describes current research at the Image and Vision Lab. of CCADET, UNAM, where we develop automatic image analysis software and 3D models of soft tissue organs for computer assisted surgery training and monitoring.

We have reported a computer model of the prostate that is the basis for the development of a real-time virtual reality simulator for TURP training.. The prostate model is constructed from a set of ultrasound images which can be manually or automatically annotated. A 3D volumetric mesh of the prostate is constructed through sampling of the set of annotated contours. The method allows for control of visual realism of the 3D mesh with appropriate time response, by varying its sampling parameter α (radial sampling angle).

The model is able to reproduce tissue resections of different sizes, depending on the cutting radius of the resectoscope. Along with resections, the model simulates in real-time tissue deformations and the global collapse of the prostate capsule as the resection of the adenoma progresses.

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From Puma of Unimation 6000 Robot to Tonatiuh Robot and Hand Free Navigation System.

Laparoscopic assistant 1996-2003

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Abstract

Objective: We describe the technological development and the surgical applications on surgical robotics builted in Mexico. The robots have been designed to assit the endocopic surgeons with robots to hold and to position laparoscopes since 1996 to 2003.

Material and tools: Two Mexican Institutions have been participated in the technological development. The Escuela Superior de Ingeniería Mecánica, Eléctrica y Robótica, ESIME, Unidad Azcapotzalco of the Instituto Politécnico Nacional. The Centro de Investigación y de Estudios Avanzados CINVESTAV of the Instituto Politécnico Nacional, was the second. In the ESIME the Industrial Robot Puma Software of Unimation 6000 of six degrees of

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freedom was mdified for four undergraduate Students. With the new Robot software had the next surgical tasks: The robot holds and position the laparoscope to be manipulated by a remote assistant surgeon. At the CINVESTAV was builted a surgical robot of four degrees of freedom and a harness (Electromechanical system). The last device is mounted on the surgeon's thorax. Both robots hold and position laparoscopes.
Results: Three cholecystectomies were carried out with the industrial PUMA 6000 robot on pigs on June 12 1996. The robot was telemanipulated by a remote surgeon by wiring 10 mts away of the operating room. Since 1998 at the CINVESTAV it was built the first Mexican Surgical Robot to hold a laparoscopic. The human surgical experience began in November 2001. This research will be concluded in 2004. A third device with the same tasks but with a new concept in laparoscopic navigation was designed and built the CINVESTAV. An electromechanical harnes mounted on the surgeon's thorax helps surgeons to hold laparoscopes with hand free navigation.
Conclusions: With these three experiences since June 12 1996 to 2003 we demonstrated the feasibilities to design and built surgical assistant robots to hold laparoscopes in Mexico. Our participation is limited in endoscopic surgery. No complications were presented on humans in surgical procedures.

1 Introduction

After the Scott Fisher publications about Virtual reality and robots telemanipulation in th of the eighty (1986)[1], The Surgeon and Ex Colonel Richard M. Satava[2] of the USA Arr the Unites States of America, he involved the experience of the spacial technology o Nasa-Ames and Stanford University International experience to the operating rooms. T technologies were related with robotic telemanipulation to explore planets like ma visualize its surface and spatial simulation in a virtual reality field. These associa between operating rooms and the spacial technology impacted the international society were the motivation to apply surgical robotics in the battle field to treat the bleedings i war since a remote site by a remote surgeon who telemanipulated[3] robots in an ope field. These technological impacts generated many projects in many countries England, France, Japan etc. Reseachers in many countries developed robots to specialties. The first surgical speciality was the war surgery (Green Telepresence Sys followed by orthopedic surgery (Orthodoc and Robodoc[5]) and neursorugery (Neuromate[6])

In 1991 AESOP 1000 Robot in laparoscopy was designed and built by Jonathan Sackier Yulung Wang[7]. Up to day each speciality shares surgical robots to assist or to perf surgical procedures. For instance, important developments are the different internati socities to promote and discuss the current developments in Computer Assisted Surg Medical Robotics such as: International Congress and Exhibition on Computer Radiology, Medicine Meets Virtual Reality MMVR, Computer Maxilofacial Congress, International Workshop. Computer Assisted Surgery CAS, Rapid Proto Medicine, Annual Conference of the International Society for Computer Aided ISCAS, International Conference on Medical Image Computing and Computer-Assis

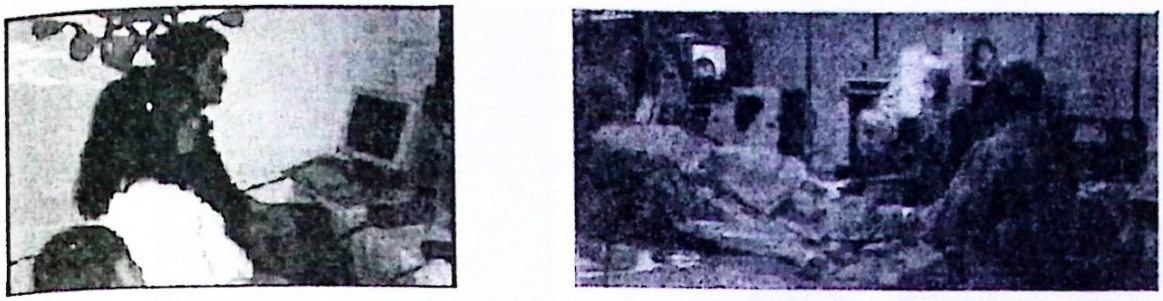
icture 1. Robot Puma de Unimation 6000, 1995. Escuela Superior de Ingeniería Mecánica, Eléctrica y Robótica Unidad Azcapotzalco IPN, Computer Integrate Manufacture Laboratory

Items	Puma	Tonatiuh
Reach (mm)	400	40
Payload (kg)	6	0.3
Axes	6	4
Applications	Industrial purpose	Surgical assistance
Electrical leakage protection	None	Yes
Clean room dedicated	No	Yes
Surgical ergonomics	No	Yes
Surgical security	No	Yes
Reverse engineering	No	Yes
Manipulation	Manual	Manual, pedal
Mechanical weight (kg)	Over 200	18

able 1. Robot specifications. Puma Robot 6000 of Unimation description vs Tonatiuh Robot ESIME Azcapotzalco 1996/ CINVESTAV 2003

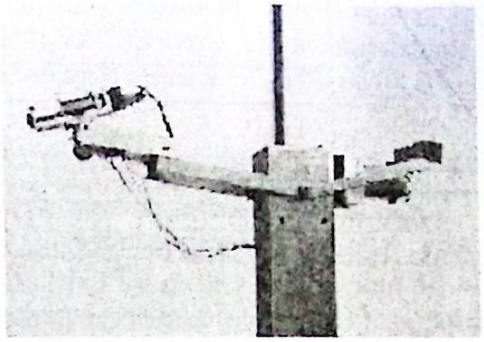
ention MICCAI, Israeli Symposium on Computer-Aided Surgery, Medical Robotics, edical Imaging ISRACAS, International Workshop on Computer- Aided Diagnosis, International Symposium on Cardiovascular Imaging, Mexican Symposium on ter Assisted Surgery and Medical Images Mexican CAS, Mexican Symposium on ter Assisted Orthopedic Surgery Mexican CAOS, etc.

Mexico since 1995 Mosso et al performed the first Robotic surgical procedures in a niversity. Undergraduate students created a specific computer program to change the dustrial tasks of a Puma Robot. The goal of this project was to design motions that permit



a b

Picture 2. Puma Robot Unimation 6000. June 12, 1996 ESIME Azcapotzalco of the IPN. a) Remote room b) Operating room in the Manufacture Computer Integrate Laboratory.



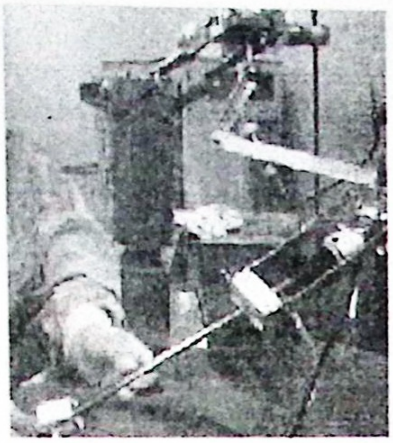
Picture 3. Tonatiuh Robot, first version.1997. Centro de Investigación y de Estudios Avanzados of the CINVESTAV IPN Bioelectrónic Laboratory.

the end effector of the PUMA navigate in abdominal cavities with a laparoscope in laparoscopic surgical procedures.[8,9] . After these experiences in 1996 we had the purpose to built a specific manipulator to hold laparoscope and the first design was Tonatiuh. It was created from 1997 to 2003. The first robot built in Latin America. It was built by Mosso and Minor at the CINVESTAV in Mexico City[10]. In 2000 we designed a third electromechanical with a new concept in endoscopic navigation. All robotic systems are installed around the patients, over the patients and inside patients. This new models is mounted on the surgeon's thorax. The harness is light, and easy to manipulate and with all possibilities to be robotized. The last two manipulators are been improved to obtain better clinical overcomes.[27-31].

2. Material and tools

Puma Robot (1995)

Four undergraduate students of the ESIME Azcapotzalco in 1995 were coordinates to develop a computer program to manipulate an Industrial Puma Robot to perform surgical tasks in laparoscopy, see picture 1. In 1996, Puma manipulator has six degrees of freedom and was teleoperated 15 m. away by a remote surgeon by wiring. See picture 2. Industrial robots were like robot a prototype to designs surgical robots. Puma characteristics are in table 1.



Picture 4. Tonatiuh Robot , 2th versión 1999. CINVESTAV IPN, Surgery Departament at the Escuela Superior de Medicina of the IPN

Picture 5. Tonatiuh Robot, 3th versión 2000. CINVESTAV IPN, Surgery Departament, Escuela Superior de Medicina of the IPN

3 Pigs	Laparoscopic cholecystectomies assisted by a teleoperated robot

Table 2. Puma Robot of Unimation. Surgical procedures in animals ESIME Azcapotzalco June 12 1996

Tonatiuh Robot (1997-2003)

Mosso and Minor in the Bioelectronic Laboratory at the CINVESTAV began to design a surgical robot in 1997. This project was accepted by CONACYT (Consejo Nacional de Ciencia y Tecnología). We modified five times the first version (see table 1) to improve motions, accuracy with surgical procedures in laboratory with experimental animals[12.] , The Tonatiuh Robot (Sun God in Aztec civilization, and founded in the center of the Aztec Calendar) has 18 Kg of weight and the computer is included inside the base of the robot. The first interface to manipulate the robot was a Keyboard. Currently is a manual control.

Hand Free Navigation System (2000 – 2003).

We describe the third navigation system developed in Mexico, a novel device to hold the laparoscopic camera during surgery (It is not a robot). Unlike other systems, it is worn by the surgeon on his thorax and its position is controlled directly by the surgeon´s body movements or by a joystick. The laparoscope holder consists of two parts: An electromechanical arm and a harness to hold it and mounted on the surgeon's thorax. In the last extreme of the portalaparoscope is installed manually, the laparoscope with a clasp and in the other extreme it has a spherical joint that provides a circular motion to the laparoscope.

Instituto Politécnico Nacional	Escuela Superior de Medicina 2001	Dogs 1 Left Hemicolectomy 1 Laparoscopy 1 Thoracoscopy 1 Transthoracic Vagotomy	4
ABC Hospital	Centro de Investigación y capacitación quirúrgica. Brimex II 2003	Rats 2 Uterine anasthomosis 1 Funduplication 360° Pigs 1 Intestine suture 1 Cholecystectomies 1 Gastroyeyuno-anastomosis	6
Total			10

Table 3. Experimental animals with Tonatiuh Robot

We designed and built in 2000 the first model to hold and place the laparoscope, it was built in acrylic, aluminum in the bioelectronics laboratory, and is composed of two parts. The system was designed and built in the bioelectronic laboratory in the Cinvestav and the surgical procedures at the Escuela Superior de Medicina of the IPN (Instituto Politécnico Nacional), on June 21, 2001. In February 2003 we carried out the first surgical experience humans.

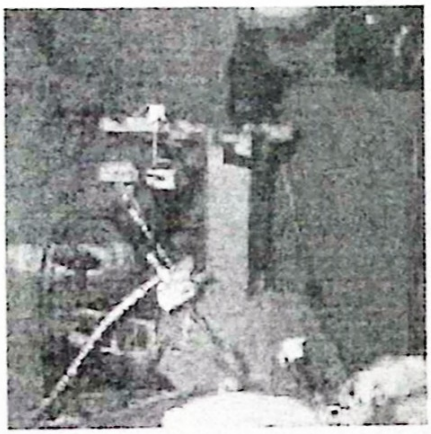
3. Results

Robot Puma (1995-1996).
We performed the first surgery assisted by a Industrial Puma Robot at the Manufactured Assisted by Computer in the ESIME Azcapotzacol of the Instituto Politécnico Nacional México city on June 12 1996. We performed three laparoscopic cholecystectomies without intraoperative complications. The robot was telemanipulated 10 m. away from a remote room. See picture 2. A Surgeon Resident was graduated at the Juárez Hospital SS, with registry number HJM – 221/ 96. Four undergraduate students in electronic engineering were graduated.

Robot Tonatiuh (1997-2003).
In the surgical department at the Escuela Superior de Medicina of the Instituto Politecnico Nacional in 1999. See pictures 4 and 5, and table 1. On November 30 2001, the first human procedure was performed. Tonatiuh Robot assisted a Vaginal Endoscopic Hysterectomy at the Hospital Regional de Troncoso of the IMSS. No complications were presented in the perioperative times[12], see picture 6. With these improvements we continued surgical procedures on humans in gastrointestinal laparoscopic procedures in 2002 at the Hospital

Picture 6. Tonatiuh Robot, 3th version 2001. CINVESTAV IPN Surgery Departament. Hospital Regional de Troncoso of the IMSS

Picture 7. Tonatiuh Robot, 3th versión 2002. CINVESTAV IPN Surgery Departament, Hosp. Fernando Quiroz Gutiérrez of the ISSSTE

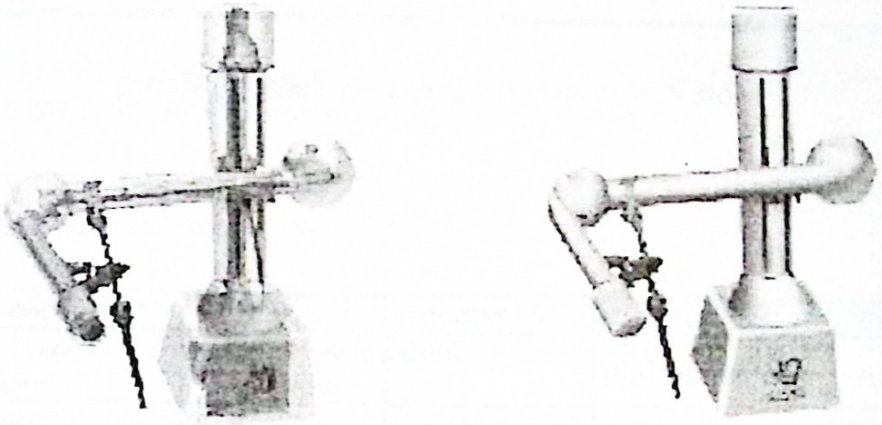


Picture 8. Tonatiuh Robot, 4th version 2002. CINVESTAV IPN-ISSSTE. Laparoscopic surgery teleguided via satellite. Hospital Belisario Domínguez Tuxtla Gtz. of the ISSSTE Chiapas

Fernando Quiroz Gutiérrez of the ISSSTE, see picture 7. On Abril 11 2002 two laparoscopic cholecistectomie at the General Hospital in Tuxtla Gutierrez City in Chiapas were teleguided via satellite by a remote surgeon located in Mexico City (National Medical Center November 20 of the ISSSTE), 2400 Km away from the operating room. The remote surgeon gave a second surgical opinion only. The surgeon was assisted by the robot inside the operating room.[14] See picture 8 and 9. At the Hospital general de zona No. 27 of the IMSS we presented the last versión of the Robot Tonatiuh. The particular modifications are been done in the Surgical training and research center Karl Storz Brimex II of the ABC Medical Center, see picture 9b and 10. This robot is the first designed and built in America Latina and was supported by the Consejo Nacional de Ciencia y Tecnología (CONACYT) from Mexico. The Registry Number is 34989-A. The robot is not finish yet. Is necessary to conclude perform

a b

Picture 9. Tonatiuh Robot, 4th version 2003. CINVESTAV IPN. a) Centro Nacional de Rehabilitación. Tirad Mexican Simposium on Computer Assisted Surgery CAS. b) Hospital ABC



Picture 10. Comercial prototype of Tonatiuh 2004. CINVESTAV IPN- SESA DE COMUNICACIONES AC. de CV.

more surgeries to validate its capacity to assist surgeons to move laparoscope. More than 2C Mexican surgeons participated in this project together with anesthesiologists, nurseries residents and Universities students in medicine. All thesis of Engineering area 7 postgraduate students (Master of science) and 1 doctoral student in bioelectronics are in process o graduation.13 publications in Mexican journals and 8 in conference were presented[8-27]. See table 4.

Hand Free Navigation System (2000 – 2003).

A new navigation system was built in laparoscopic surgery to be mounted on the surgeon thorax. The system caused fatigue to the surgeon when he could not obtain a good position t control the scope. The best advantage of the system is the speed to manipulate the laparoscop by the surgeon over the employed with human assistance to hold the laparoscope. The weigh of the system is 2.78 kg without the laparoscope. Total weight is 3.320 kg. The system was tested by surgeon initially in the physical laparoscopic simulator. We followed with surgery on dogs.

IMSS	Hospital Regional Troncoso Hospital General de zona de no. 27	1Vaginal Hysterectomy 8 Cholecystectomy	9
ISSSTE	Hospital Fernando Quiroz Gutiérrez CMN 20 de Noviembre→ Hospital Belisario Dominguez. Tuxtla Gutiérrez Chiapas	2 Cholecystectomy 1 Seromiotomy 2 Funduplication 2 Cholecystectomy	7
SS	Hospital Juárez de México Hospital Infantil de México	1 Laparoscopy 1 Funduplication 1 Gastrostomy 1 Piloroplastie 1 Esplenectomy	5
TOTAL			21

Table 4. Humans Surgeries with Tonatiuh Robot

Year	Thesis	Grade	Profession	Institution	Section	No.
1996	Thesis	Medical speciality	General surgeon	Hospital Juárez de México	Surgery department	1
1996	Thesis	Undergraduate	Industrial Robotic Engineer	ESIME Azcapotzalco	Manufacture Laboratory Assisted by Computer	4
2000	Thesis	Postgraduate	Master in science. in Bioelectrónic	CINVESTAV	Bioelectronic laboratory	1
2003	Thesis	Postgraduate	Master in science and Doctoral science	CINVESTAV	Bioelectronic Laboratory	6 1
Total						12
Journal Publications						13
Conference publications						8
Total						25

Table 5. Scientific production

4. Conclusions

The majority of surgical specialities are supported by robots to assist, or perform specific surgical tasks in operating field. Mexican surgeons, anesthesiologists, nurseries participated. Two universities, four Mexicans Public health Mexicans Institutions and one research center participated. Our principal contribution in endoscopic navigation is the electromechanical devices mounted on the surgeon thorax. This is a real artificial third arm to hold the laparoscope where the man-machine relationship is closer.

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Hand Free Navigation System In Laparoscopy. Surgical Experience

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Abstract

Objective: We describe the second navigation system developed in Mexico, a novel device to hold the laparoscopic camera during surgery. Unlike others systems, it is worn by the surgeon on his thorax and its position is controlled directly by the surgeon's body movements or by a joystick.
Material and Methods: The laparoscope holder consists of two parts: an electromechanical holder arm and harness to hold it and mounted on the surgeon's thorax. Electromechanical holder arm. In the last extreme of the portalaparoscope is installed manually, the laparoscope with a clasp and in the other extreme it has a spherical joint that provides a circular motion to the laparoscope. We designed and built in 2001 the first model to hold and place the laparoscope, it was built in acrylic, aluminum in the bioelectronics laboratory, and is composed of two parts. The system was designed and built in the bioelectronic laboratory in the Cinvestav and the surgical procedures at the Escuela Superior de Medicina of the IPN (Instituto Politécnico Nacional), on June 21, 2001. In February 2003 we carried out the first surgical experience on humans.
Results: It was possible to navigate in six directions: inside, outside, to the right, to the left, up and down inside the abdominal cavities in experimental animals. Advantages, The motions were developed succesfully and more easily by the surgeon's body aided by himself or by the physical joystick to place and position the laparoscope. We performed 4 cholecystectomies, 2 with traditional laparoscopic surgery and 2 were assisted by an electromechanical arm.The time was shorter with the technique assisted by the new device. There were discrete movements of the images displayed on the screen caused by involuntary movementes of the surgeon due to itching, coughing, sneezing, breathing, talking, being distracted chatting,

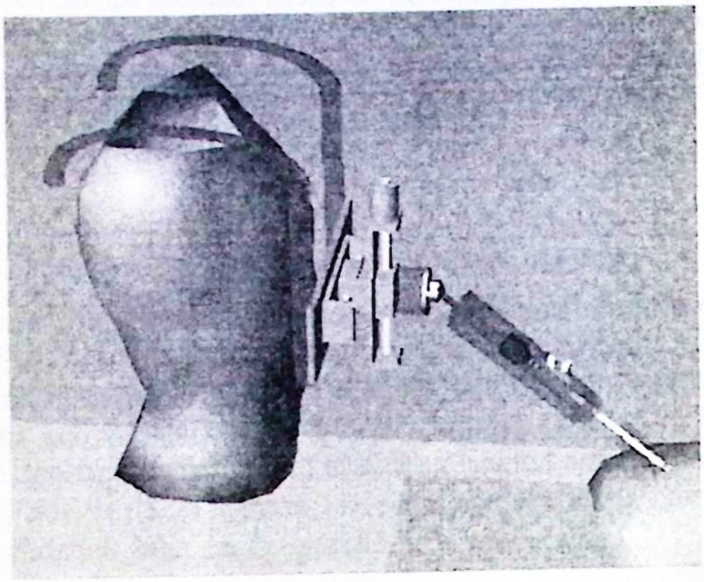
Discussion: We consider that the system can be better, to avoid contamination we can sterilize submerging the portalaparoscope in special solutions and the rest of the equipment we can cover with sterile plastic. The system provides better hand -eye coordination and positioning during surgery and to improve accuracy. We could integrate voice recognition to control the mechanical arm and exist all possibilities to be robotsized, it would be lighter.

1. Introduction.

There are several robotic arms that have been created since the beginning of 1990, with different models, characteristics applications and versions. Many of them are in experimental or in laboratory areas and others are in commercial developing process. The surgeon has looked for devices and systems in order to control absolutely the laparoscope and avoid the limits of verbal communication with the human assistance during the navigation. There are robotic arms to be applied in the next areas: Neurosurgery (Minerva) (1), Neurobot, Orthopedic (Orthodoc) (2), Robodoc, Caspar (3), laparoscopy (4), (Aesop) (5,6), Lars, laparobot, Zeus, da Vinci (7), and radiotherapy. These systems can be passive, semiactive and active devices, and can be controlled by different interfaces: voice recognition, phyisical joysticks, head motions, robotic vision, pedal, data gloves, control feedback (8), optical zoom (9) to have better motions that are built with 4,5,6,7, or 8 joints. The functions are different depending of the surgical area. For example: in orthopedic surgery (to plan the surgery, to perfom the medular duct, to place the prothesis) in laparoscopy (to place and position the laparoscope, to take biopses, to process surgical images). The robotic arms can be controlled in the same place (Operating room) or from a distant operating room (telesurgery). The surgeons can manipulate the robot with the next objectives: to plan, to assist (10), to guide and to perform the surgery. The surgeons can manipulate robots with different applications like: surgical education, and aid to surgeons. There are different areas that integrate the medical robotics (11): computer, mechatrionics (12) engineering, surgery, robotic. None of these systems are mounted to the surgeon's body. The great limitations of these new technologies are found in the majority of the hospitals in the world. These limitations are the cost and the volume of the equipment necessary in the operating room, moreover the specialized people have to adjust the robotics systems maintaining the good functioning of the equipment. Our particular search in the navigation area has permitted us go in the area of the development of robots to perform the navigation, exploring the voice recognition, keyboard and joystick to the manipulation, trying to find our solutions. On June 12, 1996, we performed the first surgical robotics experience in Mexico (13), in 2000 we constructed the first robotic arm to hold the laparoscope (14,15).

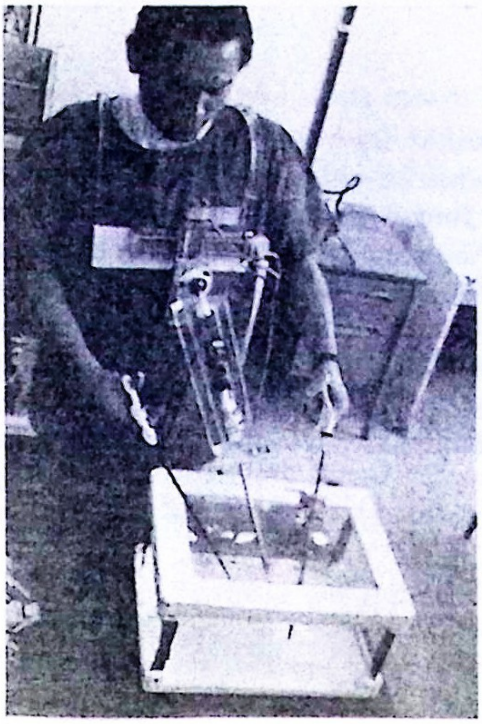
2. Material and methods

The harness has a passive and spherical joint (Rotula), and this joint joins a laparoscope holder using an aluminum plate.The system is installed manually in the last extreme on the laparoscope holder with a clasp and in the another the joint is attached in two linear rails and these in an acrylic and aluminum square platform (placed on the surgeon's thorax) (Picture 1,2). And this plate can move or slide with rails, up, down, over the harness. The system is complemented with servomotors, making it active. With these characteristics or options, the system adjusts



Picture 1.- Virtual model of the Hand free navigation system. Lateral view.

according to the surgeon's physique. Moreover to place the laparoscope in the surgical field and avoid efforts. In both versions, the harness permits the manipulation with hand-free navigation (HFN) to perform the surgery, without limiting the surgeon's field. The espherical joint provides a circular motion to the laparoscope and all system acquire more degrees of freedom. The laparoscope moves inside the cavity taking as the point of support the sliding of the abdominal wall independently of the deep inside the cavity. Moreover it permits the required angular slide in any plane. In the X axis more or less 50 degrees since a frontal point insertion and for the Y axis more or less 30 degrees and the same complementary movements in the cavity space. The results of the angular slide increase according to the change of the surgical body in any direction, increasing the visual space to the procedure. The spherical joint has a minimal mechanical friction to avoid unnecessary efforts, permitting the surgeon to attach or unattached easily the laparoscope to the harness during surgical procedures. The harness has an electromechanical device on its frontal surface with a linear slide that has two degrees of freedom. This control permits the surgeon to make a minimum effort to replace the laparoscope inside the cavity and it becomes an ergonomic system. We used two motors of direct electrical current of gear-transmission and the adaptation was performed by PWM (pulse width modulation) and provide motions to the laparoscope in two planes, in vertical and horizontal sense. This permits a successive approximation with the electromechanical system of 0.1 mm . The speed in each axis was 2.5 cm a second with a longitude slide of 19 cm, and in the motors' activation in the experimental test we employed the keyboard. The weight of the system is 2.78 kilo (6.12 lbs) without the laparoscope (160 grs.) and the micro camera (380 grs.). In total weight is 3.320 kilo (7.304 lbs).The system was tested by the surgeon initially in the physical laparoscopic simulator. It performed movements with chicken pieces to evaluate the motions of the system. Once the manipulation and acquired experience with the system with hand-free navigation had been verified. We followed with surgery on dogs. The surgeon wore the system mounted on the harness on the thorax with the help of an engineer.



Picture 2. Hand Free Navigation System, mounted on the surgeon´s thorax. Bioelectronic´s laboratory at the (Centro de Investigación y de Estudios Avanzados) CINVESTAV. Mexico City.

The surgeon performed the HFN initially with the body motions. Later the slide laparoscope is complemented with the electromechanical system. In both X and Y axes a keyboard was used. Finally the system is disarticulated by the surgeon with the help of the engineer. The surgeon could navigate in the X axis 200 degrees and with the Y axis give or take 40 degrees. The depth of the insertion was not limited by the surgeon and he had no pain. The spherical joint and the abdominal wall as a point of support permits an ideal linear slide in the cavity. The harness system permits the surgeon to connect or disconnect with the sensorial surgical universe around him such as tissues and organs. The laparoscope connection or disconnection with the harness demonstrated that it is vital to perform quickly the next tasks. The fast-port insertion, initial laparoscope insertion and laparoscopic cleaning, permit the performing of the surgical procedures with continuity. This system avoids changes in the surgeon´s position or on his body. The complementary electromechanical position permits a good relationship between the surgeon and the organs, and this complement permits fast access and security as the surgeon performs the approximation with his body motions. We designed and built the system in the bioelectronics laboratory in the Cinvestav (Centro de Investigación y Estudios Avanzados) of the Instituto Politécnico Nacional. We performed three laparoscopic surgical procedures assisted with the hand free navigation system. With the engineering attendance the surgeon placed on his thorax a device then the engineer placed the arm to the device and finally the laparoscope to the arm but previously the laparoscope was inserted to the abdominal cavity. With the system total installation the surgeon performed the navigation manipulating the laparoscope in the beginning with the corporal motions then with the physical joystick. The surgeon dissected the gall bladder and the cystic vessels were dissected and clamped. Finally the system was disarticulated with the engineer in attendance and with the first assistant.

3. Results

A new navigation system was built in laparoscopic surgery to the surgeon's thorax. The system caused fatigue to the surgeon when he could not obtain a good position to control the scope requiring a spinal flexibility for long periods. The best advantage of the system is the speed to manipulate the laparoscope by the surgeon over the time employed with human assistance to hold the laparoscope. We removed the gall bladder also to clamp the cystic duct and blood vessels.The manual control was employed less and the device's motions were slow. The system offered a better speed of manipulation because the surgical time was reduced when we employed it. With the human assistance the surgical time was 45 minutes and with the device 27. The capacity of motions and thus a better accuracy and security to patients.

4. Discussion.

We present a new concept of endoscopic manipulation or navigation as well as a generic idea for its multiple uses in different surgical areas where fiber optics such as arthroscopy, neurosurgery, laparoscopy, urology, gynecology (16,17) etc. are used. The electromechanical arm once it is articulated to the surgeon's thorax offers more degrees of freedom to the human's arms that due to their nature have a redundancy sufficient to survive, not so the robotic arms that for economical reasons are built with a limited redundancy. From there, the described system offers possibilities to interact with the surgical work field, also a better hand-eye coordination, and the man-machine relationship is closer. However it presents disadvantages that would better with time like: fatigue positions or when there are involuntary movements such as itching, coughing, sneezing, breathing, talking, being distracted chatting, and the surgeon's body movements which were stabilized or decreased thanks to the stability given by the spherical articulation of the rotula maintaining this way an effective hand-eye coordination. It is possible to build a lighter system, to add voice recognition to control the mechanical arm or attach to the surgical instruments, including to robotize the system. We suggest employing this system in shorter surgical procedures or when the circumstances require accuracy with the tool manipulation. The designed system is an alternative navigation with free hands in laparoscopic surgery and it permits a faster relationship with the tissues and organs than robots do. This is the second navigation system developed totally in Mexico. This system was presented in 6th International Workshop CAS 2001, Computer Assisted Surgery and Rapid Prototyping in Medicine, Nuremberg, Germany (18).

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This book presents a compilation of the papers presented at the EU-LAT Workshop on e-Health, held in Cuernavaca, Mexico on December 2003. EU-LAT (IST-2001-32792) is a FP5 EU funded initiative to bring together research groups from Europe and Latin-America and to create the conditions for them to build new research proposals. The quality and quantity of the work shows that *e*-Health is a very active and strong area of research in both sides of the Atlantic Ocean. It is clear that any improvement in the standards of Health services will be well received by society.

Six topics are covered in this book: *Software Agents in Health Care, Information management and delivery*, *Mobile Computing and Ambient Intelligence, Data Analysis and Knowledge Discovery*, *Task Planning and Scheduling* and *Imaging, 3D Models and Surgery*.

We are very glad to show the ongoing work on *e*-Health and to serve as stepping stone for new ways of cooperation.

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