Formations in Collective Robotics

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Abstract. In this paper, the problem of coordination of groups of robots or agents that have to arrange themselves in spatial formations is addressed. The designing and implementation of mechanisms to enable a group of agents to create and keep formations is important for a number of applications such as collective exploration and monitoring of environments. Three models for the generation and keeping of formations using, respectively, semi-autonomous, composed autonomous and simple autonomous agents are presented and compared.
key words: agent, simulated robot, formations, spatial patterns.

1 Introduction

Collective robotics is interested in designing systems consisting of various robots able to solve problems jointly. The robots taking part in a multi-robot system are homogeneous, simpler in terms of design and control, and cheaper than specialized single systems. Multi-robot systems are oriented to solve problems in which the participation of a single robot is not sufficient or is very expensive, in terms of design and time for example, such as transportation of voluminous objects, hazardous material handling, environment exploration, monitoring and terrain coverage.

The design of mechanisms to enable groups of robots to generate and keep spatial formations is a line of research in the vast field of collective robotics. A formation is defined as a spatio-temporal structure constituted by a set of robots where each one represents a point or vertex of the structure. The design of multi-robot systems presents significant challenges. When a group of robots shares a common space work, each member of the group is a mobile obstacle for the others. In order to avoid this problem, coordination is required among robots. Multi-robot coordination consists in synchronizing the respective individual movements of the robots, in such a way that they execute their tasks avoiding collisions.

The rest of this article is organized as follows: Section 2 outlines related work, section 3 describes our proposal and methodology to generate and keep formations, section 4 discusses experimental results, and section 5 addresses conclusions and perspectives of the project.

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2 Related Work

The organized behavior exhibited by certain animal groups such as flocks, fish schools, army ants and the spontaneous formation of structures such as the rays in a zebra or the structure of the DNA involve mechanisms of self-organization and coordination [1].

With the purpose of studying self-organization, artificial colonies called multi-agent systems have been created. An agent is an autonomous virtual robot which is able to perceive its environment and to act on this.

Some mechanisms that have been proposed for self-organizing multi-agent systems are described below.

Reynolds [2] developed a simple egocentric behavioral model for flocking which is instantiated in each member of a group of simulated agents called *boids*. Reynolds' boids keep proper position and orientation within the flock by balancing their tendency to avoid collisions with neighbors, by matching the velocity of nearby neighbors and moving towards the center of the flock. The rules that these boids apply are very simple, e.g. avoid collisions, copy other boids' velocities and directions, search the center of a group and move laterally away from any boid that blocks the view. An important contribution of Reynolds' work is the generation of apparently orchestrated collective behavior in agents from local perception-based rules.

Another example of systems that work cooperatively in the construction of collective structures is Resnick's termites [3]. He proposed simple rules such as wander, carry and drop objects in order to obtain large groups of agents that cooperatively build structures that appear to have some sort of planning behind them. Resnick's termites wander randomly until they bump into a piece of wood. If a termite is carrying a piece of wood when it bumps, it drops the piece and continues to wander. If the termite is not carrying any piece, it picks up the one it bumped into and continues to wander.

Sugihara and Suzuki [4] performed experiments with multiple simulated robots that are able to form stable formations when each robot executed an identical algorithm for position determination within a group. Each robot of the group is able to perceive the relative position of all other robots and to move one grid position each time. Regular geometric shapes such as a circle can be formed by these robots.

Ünsal [5] developed an algorithm for self-organization of ants' colonies or multi-agent systems, where the agents are identical both physically and functionally. Each Ünsal's agent has limited capabilities and limited knowledge of the environment, but as a colony, they exhibit an intelligent behavior.

Ünsal's algorithm is based on beacon recognition, where beacons are used to identify the meeting point of agents. With this algorithm, separated groups of agents around several beacons are formed. An agent approaches the beacon until it is within a predefined distance d in a vicinity $d + \varepsilon$. If any agent is within the area defined by $d - \varepsilon$, it is rejected by the beacon. Within the ε area, each robot moves far away from their closest neighbor therefore creating formations such as circles, spheres and paraboloids.

Balch and Arkin [6] present several formations for a group of four robots such as: lines, columns, diamonds and wedges. These formations were tested using both simulated and physical robots. For each formation, each robot has a specific position based on its identification number (ID). These behaviors are identical for each of the four robots, except for a robot who is designated as the leader. The tasks of each robot are to move towards a goal location, avoid obstacles, avoid collisions with other robots and keep the original formation. Dynamic formations are kept through two steps: First perception process, here, the robot's proper position in a formation is determined based on its current environmental perception. During, the second step, the motion process, motion commands are generated in order to guide a robot towards its correct location. Each robot computes its proper position in the formation based on the other robot locations.

Mataric [7] uses a simple, general formation algorithm based only on local sensing and control. This algorithm has been tested using both simulated and physical robots. Each robot in the formation is autonomous and has no information about other robots. Each robot has an ID that is broadcasted regularly as a message. Robots' IDs are detectable by other robots. The robot that is located in front of the formation is considered the leader and any robot can take this role. Every robot knows at any time the total number of robots participating and the kind of formation they should have. Except for the leader, each robot follows a designated neighbor known as its friend, keeping certain distance and angle with respect to its heading. Every robot has at most one follower, except for the leader which can have one or two. In this way the robots connect in a "chain of friendships".

3 Proposal

In this section, a serie of experiments using simulated robots that have to form spatial formations is described. Two kind of formations were studied with the purpose of developing mechanisms to coordinate the collective exploration of large environments: static and dynamic. Static formations are generated by immobile agents, whereas dynamic formations are kept by mobile agents.

Experiments were performed on StarLogo ©, an environment of simulation developed at MIT by Resnick [8].

3.1 Agents

Three different agent models were studied in order to test the abilities required to generate and keep formations.

The first agent model was a **semi-autonomous agent**. This agent is a point in a two-dimensional space, it can move a certain number of positions and change its direction in a given angle. Semi-autonomous agents are also able to directly transmit their position to other agents at any time. The generation of a formation is based on this information, that is supposed to be transmitted and received without error. Because agents depend on this information and are unable to collect it by themselves, they are considered semi-autonomous. The agents have a radius of perception and information transmission of two positions in the environment (see Figure 1 a)).

The second model is denominated **composed autonomous agent** and was proposed to improve the first model. As semi-autonomous agents are unable to distinguish their partners, by themselves, agents were redefined to be able to perceive locally this information. A composed autonomous agent is a multi-agent system consisting of four agents: a head, a center and two arms. These agents are points in a two-dimensional space painted with predefined colors to identify the parts of a composed body. This information is used by composed autonomous agents to estimate their orientations. The perception of these agents is merged from the individual perception of each one of their parts. These agents do not directly transmit their position nor their direction, these are rather estimated based on the local agent's perception and the recognition of the colors that identify their bodies (see Figure 1 b)).

The third model, **simple autonomous agent** was proposed to capture the advantages of previous models. This model aims for autonomy and simplicity, as in the second and first agent models. These agents are points in a two-dimensional space. They can move a certain number of positions and change their direction in a given angle. Simple autonomous agents are painted of predefined red scale colors according to their orientation, e.g. a dark red agent is oriented towards the north, a red agent is oriented towards the east and a clear red agent is oriented towards the northwest. These agents do not directly transmit their position nor their direction, this information is rather estimated from local perception. The agents have a radius of perception of five positions in the environment (see Figure 1 c)).

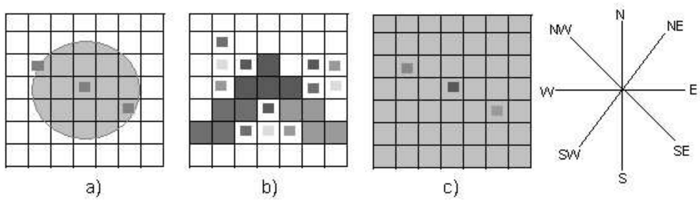

Fig. 1. Agent representation: semi-autonomous agents a), composed autonomous agents b), and simple autonomous agents c). Each figure shows an agent in the center surrounded by two agents: one oriented to the east and one oriented to the northwest. The radius of perception of the agent in the center is also indicated in gray color

Each one of the previous agents has an ID and a set of properties described in Table 1.

Table 1. Properties of semi-autonomous, composed autonomous and simple autonomous agents

Model	Perception	Action
Semi autonomous agent	Own absolute position Signals of neighbors Goal position	Move towards the goal position Transmit position Follow a neighbor
Composed autonomous agent	Own absolute position Marks of neighbors Goal position	Move towards the goal position Follow a neighbor
Simple autonomous agent	Own absolute position Goal position	Move towards the goal position Follow neighbor

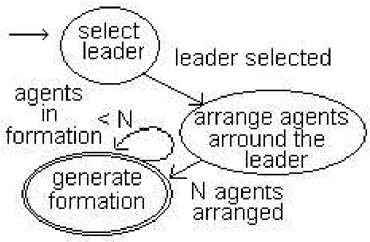

Fig. 2. General algorithm to generate static formations for N agents

3.2 Static Formations

Static wedge formations are important in applications where an exploration of the environment is required, e.g. military applications and terrain coverage.

Static wedge formations using semi-autonomous and composed autonomous agents were programmed. In order to do a wedge formation, agents have to be, arranged around a mark known as the *meeting point.* Agents must reach the meeting point in order to generate a static formation.

As soon as an agent reaches the meeting point, this agent takes the current leadership in the formation. Then, three rules are applied: first, the leader decides randomly the number of branches among 2, 4 and 6 in the formation and transmits the leadership to the agent who is in front of it and goes back two steps. Second, the other agents go towards the current leader in a succession of turns determined by their IDs. And third, if an agent who is formed perceives another agent within a predefined vicinity, it goes back two steps keeping its orientation.

Static formations using simple autonomous agents were also programmed. As these formations differ slightly from the previous ones, they are called approximate wedges. Neither arrangement around a meeting point nor communication among agents is required in order to generate approximate static formations.

Two rules are applied to generate this formation: first, agents wander avoiding collisions and turning randomly to their left or right. And second, an agent meets other agent if it is within its local radius of perception. These rules produce eventually the grouping of agents in "wedges".

The control of a group of agents whose main task is to generate a static formation is illustrated in Figure 2

3.3 Dynamic Formations

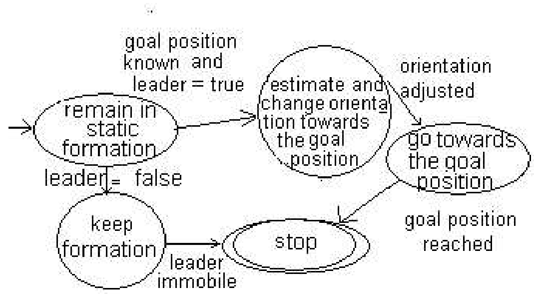

Fig. 3. General algorithm to *keepformation*. The state *keep formation* is instantiated according to the agent model (see Figure 4)

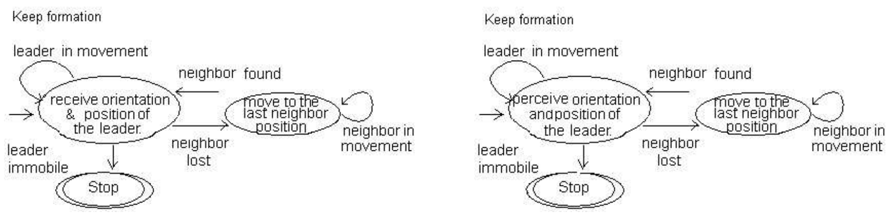

Fig. 4. Dynamic formation using semi-autonomous agents (left) and dynamic formation using composed autonomous and simple autonomous agents (right). Figures 5 and 6 illustrate the estimation of the leader's positions and orientation

Dynamic wedge formations consisting of semi-autonomous and composed autonomous agents were programmed.

In dynamic formations, a group of agents that has achieved a static formation moves towards a goal position keeping the initial formation as far as possible. If external perturbations, such as obstacles or mobile objects, force agents to undo their formation, they should know what to do in order to recover the initial or a similar formation. The control of agents that have to keep a dynamic formation in an environment without obstacles is illustrated in Figure 3.

In order to keep a dynamic formation, semi-autonomous agents have to communicate among them. Two rules are applied to keep a dynamic formation: first, the leader estimates and changes its orientation towards the goal position. Then it transmits its orientation and its movements to its partners while going towards the goal position. Second, the partners receive the leader's orientation and follow the movements transmitted by the leader (see Figures 3 and 4).

To keep a dynamic formation, composed autonomous agents have to estimate their neighbor's orientation and position by local perception from the marks on their bodies. The leader estimates the orientation towards the goal position and goes towards the goal position. Then, the partners copy their orientation and go to the last position where they perceived a partner (see Figures 3, 4, and 5).

Dynamic formation using simple autonomous agents were also programmed. In order to keep an approximate wedge formation, agents have to be arranged firstly, in a static formation. In this formation agents are autonomous, they decide their actions based on their local perception and their own estimations, e.g. the agent who is the leader estimates the orientation towards the goal position, and goes towards this position. Agents copy and follow their partners orientation that is perceived by their owns means, reforming (see Figures 3, 4 and 6).

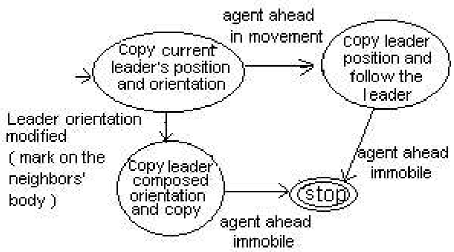

Fig. 5. Perception of the position and orientation of the leader in composed autonomous agent model

4 Experimental Results

The different agent models that were previously presented were tested in similar experiments whose purpose was keep dynamic wedge formations.

The number of agents that participate in these formations go from twenty to eighty in the experiments using semi-autonomous and simple autonomous agents and, from three to ten groups in the experiments using composed autonomous agents. The distance that agents have to move towards the goal position is about 30 steps in environments without obstacles.

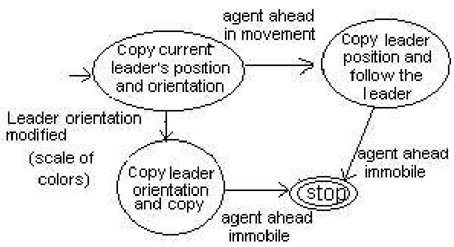

Fig. 6. Perception of the position and orientation of the leader in simple autonomous agent model

Semi-autonomous, compose autonomous and simple autonomous agents make formations having occasional leaders. They have to move comparable distances, from an initial position towards a goal position, keeping the formation. The time spent by semi-autonomous, composed autonomous and simple autonomous agents to do this task is shown in Figure 7.

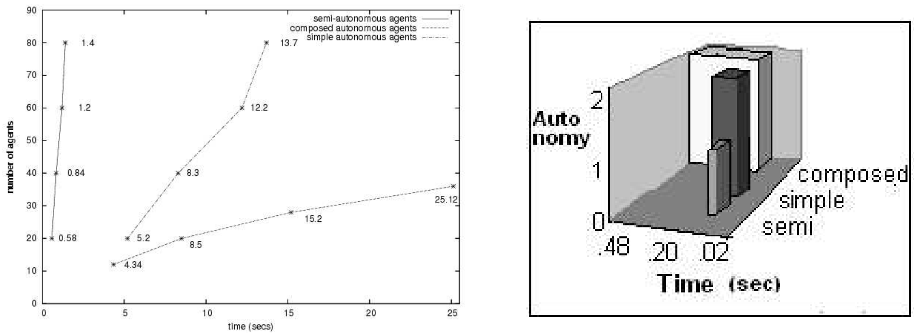

Fig. 7. Time spent by groups of agents who move from an initial position towards a goal position of the environment: semi-autonomous agents, composed autonomous agents and simple autonomous agents (left) and the time that agents of each model spend on average to do similar tasks and their levels of autonomy are compared (right)

As Figure 7 shows, the average time required for a semi-autonomous agent to keep a dynamic formation from an initial to a goal position is 0.02 secs, whereas the average time required by a composed autonomous agent to do the same task is 0.48 sec. That means that a semi-autonomous agent is in an average 24 times faster than a composed autonomous agent. This difference can be explained by the fact that the first agent does not spend time estimating the position and orientation of its partners in contrast with the second, which is in fact integrated with four agents who have to perceive their neighbors in addition to merge their perception in order to estimate their position and orientation. On the one hand,

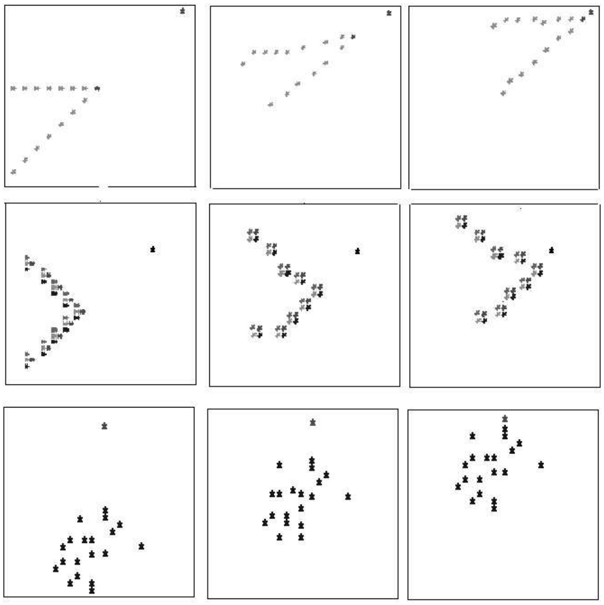

Fig. 8. Snapshots of semi-autonomous (top), composed autonomous (center) and simple autonomous (bottom) agents. Figures indicate from left to right respectively, the initial, an intermediate, and the goal position

semi-autonomous agents are faster than composed autonomous agents, but on the other hand, the second are able to operate by their own means.

Average total time was calculated from the averages spent by each group to complete a task, e.g. 0.029, 0.021, 0.02 and 0.0175 for agents of respectively 20, 40, 60 and 80 of the first model.

Figure 7 shows the performance of one agent of each model measured with respect to the time spent to do the same task and its degree of autonomy. Autonomous agents are able to operate based on their own sensor and actuators and have a high level of autonomy (2 in the graph), whereas semi-autonomous agents whose operation depends on direct communication have a medium degree of autonomy (1 in the graph). The best performing model was the third, the model that takes advantage of previous models. Simple autonomous agents are good enough to keep a dynamic formation, they are quite faster in comparison with semi-autonomous agents, and as independent as composed autonomous agents.

Figure 8 shows some snapshots of groups of agents controlled by the algorithms that were previously presented.

Local perception is not enough to enable autonomy. Agents must be externally distinguishable in order to enable them to perceive their orientation as it happens in second and third models.

5 Conclusions and Perspectives

In this paper, three different agent models, semi-autonomous, composed autonomous and simple autonomous agents, to generate and keep respectively, static and dynamic spatial formations in environments without obstacles were presented and compared.

These models were designed constructively, i.e. each model attempts to improve the previous one, taking the advantages that were detected. The third model, simple autonomous agents, was the best of the three because of its simplicity and autonomy.

The design of mechanisms to generate and keep spatial formations is important in order to define robust multi-agent systems able to transport objects, handle hazardous material and cover terrain.

In the literature, the advantages of decentralization over centralization, as well as the advantages of local perception-based systems over direct communication-based systems are taken for granted. The main contribution of this paper is the analysis of different agent model based on experimental results in order to compare their reliability.

The selection of an agent model depends on the environmental conditions, in environments where communication can be established with minimal error, semi-autonomous agents can operate efficiently, whereas composed autonomous and simple autonomous agents are better when communication is incomplete or noisy.

This work is in progress. Future work will consider richer environments including fixed and mobile obstacles, as well as mobile goal positions, and the definition of rules enabling agents to rearrange themselves in formations they were forced to undo.

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