A prototype of a new staircase climbing wheelchair

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Abstract. This paper describes the mechanical devices, the control architecture and the control strategies of a novel wheelchair prototype capable of climbing staircases. The key feature of the mechanical design is the use of two decoupled mechanisms in each axle, one used to negociate steps, and the other to position the axle with respect to the chair to accommodate the overall slope. This decoupling makes many different climbing strategies, possible making the design extraordinarily versatile. A control architecture has been developed to operate the prototype motion. Passenger comfort in the climbing movement imposes strong restrictions on the planning of trajectories. Finally, we describe the real prototype developed and we propose a way to make a calibration of the kinematic model.

1 Introduction

Wheelchairs have remained basically unchanged over the past 100 years. Most of the design changes have occurred within recent decades. The first important change was the appearance of powered wheelchairs which greatly improved the mobility of the handicapped.

The second important change occurred in the mid 1990s when the first stair-climbing powered wheelchairs appeared. However, the authors of this paper believe that most of these designs have severe drawbacks that impair their widespread use. Drawbacks are generally related to the lack of safety stemming from mechanically unstable situations during staircase climbing or descent. The mechanisms described in this paper have been designed to enforce mechanical stability while the wheelchair is on a staircase. The weight is transferred at all times to horizontal surfaces (the tread), making it unnecessary to rely on friction to ensure safety as is needed with wheelchairs based on tracks.

One may find a variety of designs in the technical literature. Some of these designs are based on several wheels arranged in a rotating link [1]. This system may work satisfactorily for the "design staircase", but proper functioning is impaired when different treads or step heights are encountered.

The iBOT 3000 [2] is a very compact design that can adjust to different step sizes. Whilst the mechanical design is quite simple, the chair is very sophisticated since it relies on dynamic control to maintain an upright position. There are motion phases during climbing or descent when the chair is standing on just two wheels with a

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common axis. The major drawback of this design is the tremendous cost necessary to meet reasonable safety standards. Another problem is that this prototype requires the user to hold on to the handrail for safe use.

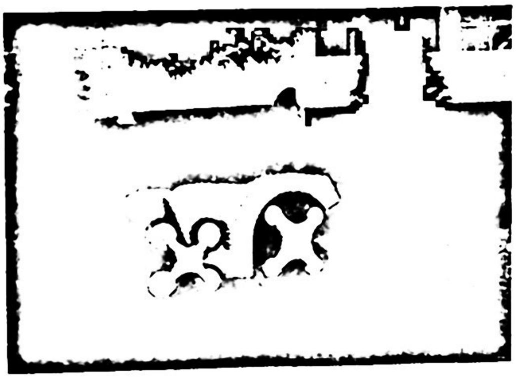

Fig. 1. Prototype from Tamagawa University. School of Engineering [1].

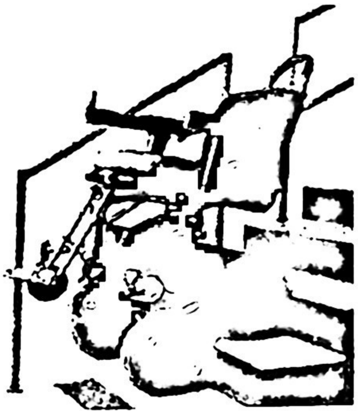

Fig. 2. The iBOT 3000 [2].

Fig. 3. Model of track wheelchair [3].

The tracked chairs [3] have, in our opinion, serious problems that impair their success. The first problem is the low efficiency of the tracks on horizontal displacement. The second problem is that the weight is supported by the vertical component of the contact force between the track and the edge of the steps. A high friction coefficient is needed to maintain equilibrium. Another problem is that entering and exiting of the staircase are difficult and dangerous processes.

Finally, the structure of this document is the following. Section 2 describes the advantages of the new prototype. Section 3 describes the tasks in which the staircase climbing process is decomposed. Section 4 shows the control architecture to operate the whole system. Section 5 is a summary of the prototype kinematic model. Section 6 shows the trajectory planning to obtain comfortable movement for the passenger. Section 7 is a description of the mechanical specifications of the new prototype and section 8 shows the conclusions that we have reached.

2. Mechanical System Description

The authors think that most of the disadvantages of the mentioned systems are due to an improper approach to the problem. The proposed design solves the climbing problem splitting it into two subproblems: front and rear axle positioning and single step-climbing. Every problem is solved by a specific mechanical device. The wheelchair described in this paper is based on these two different systems: a system to arbitrarily position both axels with respect to the frame to accommodate the overall slope (Fig.

4), and a device that makes the axel climb one step at a time while allowing the wheel to move around the step eluding interference with it (Fig. 5).

In the design of the first system (see Fig.4), both the front and the rear axles are joined to the frame by means of four link mechanisms. Each four link mechanism is driven by an independent actuator. These mechanisms are parallelograms, which means that the frames of the front and rear axle do not rotate with respect to the main frame. The overall system has two degrees of freedom which are driven with two linear actuators.

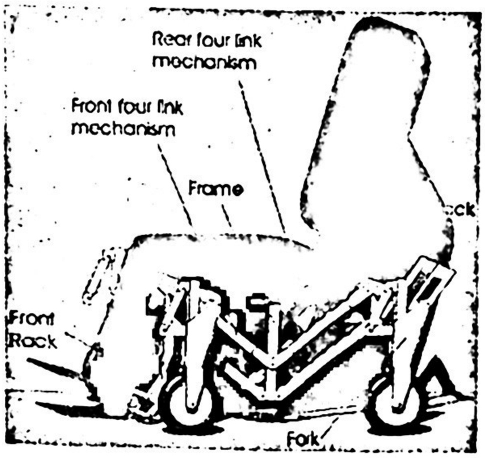

Fig. 4. Schematics of the wheelchair construction.

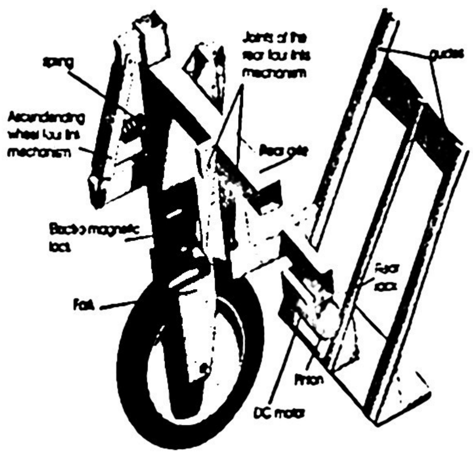

Fig. 5. Cutaway of the mechanism to climb one step.

On the other hand, in the design of the second system (see Fig.5), each axle climbs the corresponding step by deploying the rack that is connected to it. This is tantamount to saying that each axle "carries its own ladder". All steps are climbed with the same slope, and the height reached is determined by the step itself, since the wheel moves back to the initial position as soon as the step has been surpassed. This is achieved by connecting the wheel to the axle via a four link mechanism. The mechanism may be designed to guide the wheel trajectory with respect to the axle and the stability condition is rather superfluous since it is safer to lock the wheel fork in its resting position whenever needed.

Finally, in the movement of the mechanism, the system is always in stable equilibrium. This is very important to ensure safety of the system. On the other hand, in the next section it will be shown, that the proposed mechanism can be easily manufactured using mostly off-the-shelf mechanical components due to the modular design of the prototype.

3. Stages of the climbing motion for the positioning system.

Now that the mechanical system has been described, next we present the basic tasks in which the staircase climbing process is decomposed:

1. Positioning of the wheelchair with respect to the staircase (previous to the climbing process). Alignment between the rear wheel axis and the front of the lower step (Fig. 6).
2. Climbing of the rear wheels while the front wheels remain on the floor (the first few steps of the staircase, Fig. 7).
3. Simultaneous climbing of the rear and front wheels (Fig. 8).
4. Climbing of front wheels with the rear wheels remaining on the upper floor (the last steps of the staircase, Fig. 9).

More information on the stages of the climbing motion is supplied in [5].

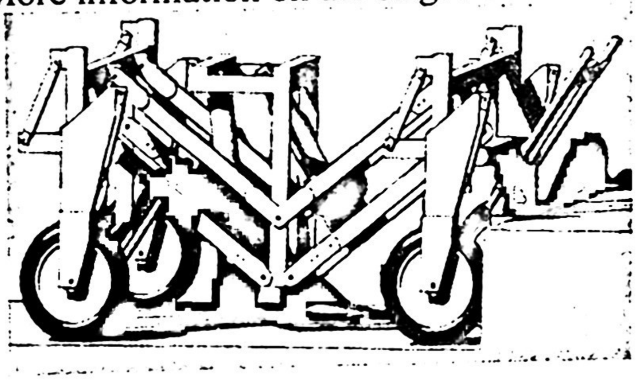

Fig. 6. Schematic view of one side of the mechanism in its position prior to climbing.

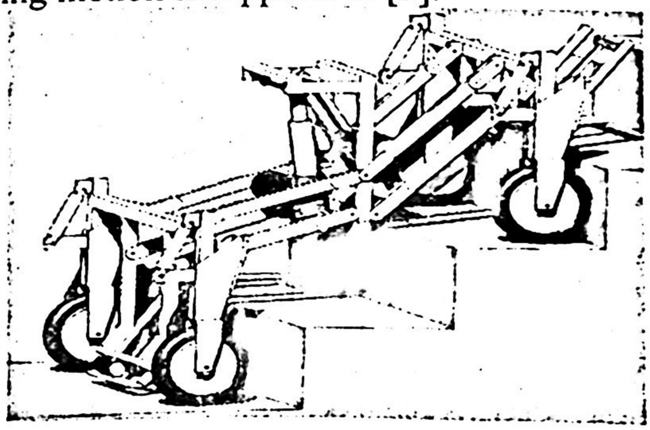

Fig. 7. The rear wheels are on the staircase while the front wheels are on the floor.

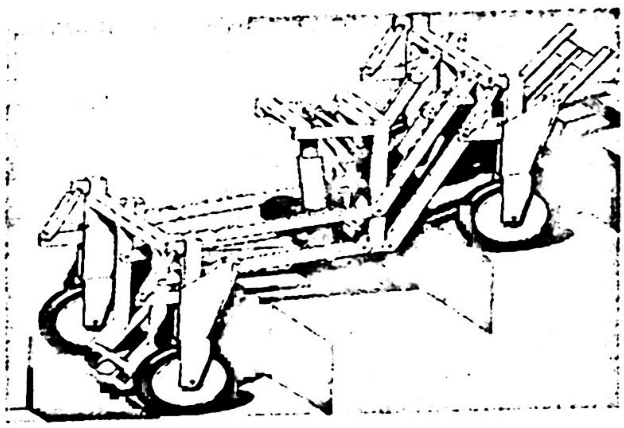

Fig. 8. Both axles on the staircase.

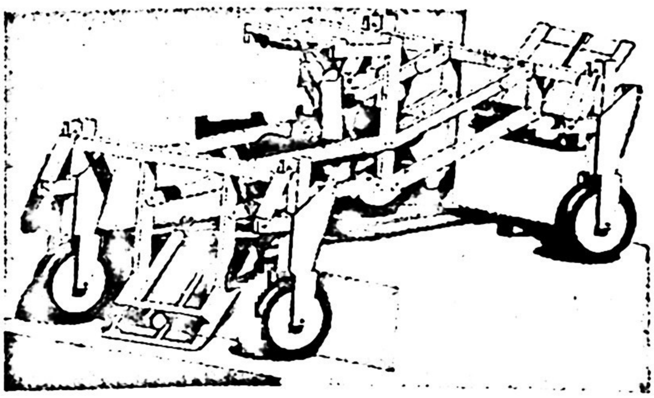

Fig. 9. The rear wheels are on the staircase while the front wheels are on the floor.

In the climbing and descent processes, the changes in the wheelchair configuration depend on the ultrasound sensor measurements. With these measurements and the knowledge of the present configuration, we can obtain the next wheelchair configuration. This is tantamount to saying that the behavior of the wheelchair is like a state-diagram. Fig. 10 shows the possible wheelchair state transitions in ascent/descent mode.

4. Control architecture

The process described has to be synchronized with axle positioning, in order to maintain the verticality of the chair frame, and in order to generate the appropriate chair frame trajectory. Moreover, the inclination is also under control, all this in order to guarantee the comfort of the passenger. Then, a relatively complex sensorial system and an accurate control architecture is needed to operate the whole system.

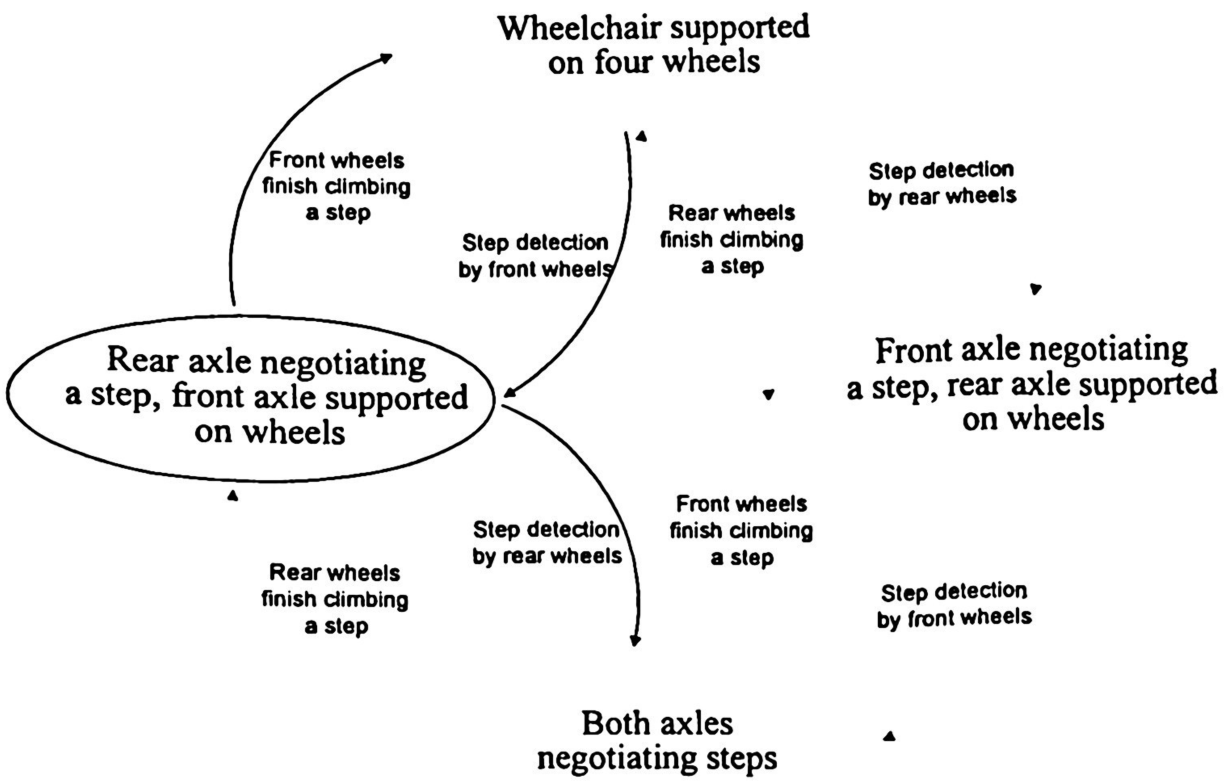

Fig. 10. Wheelchair state diagram.

4.1. Sensorial system

Various sensors are used to monitor the wheelchair movement in the climbing/descent process. They are detailed next:

- 8 ultrasound sensors (2 per wheel). They are needed to measure the distances between the wheels and the steps and to obtain information about the climbing/descent process. They are placed two per wheel in horizontal and vertical position.
- 1 inclinometer which measures the verticality of the chair and detects the instant at which the climbing mechanism touches the floor when being deployed. It is placed on the frame.
- 4 encoders for the rear wheels (2), and the racks of the climbing mechanism (2).

- 2 angle sensors to obtain measurements for the two joints connecting the chair structure with the front and rear four bar linkages.
- 4 switches (1 per wheel) that indicate the end positions of the 6 four-bar-mechanisms.
- 8 switches (2 per linear actuator and 2 per rack) to indicate the maximum and minimum position for the two joints of the chair structure for the racks.
- 4 electromagnetic solenoids (1 per wheel) to lock or unlock the mechanisms that connect the wheels to the axles.

4.2. Actuator system

The movement of the prototype is provided by two DC motors which are joined to rear wheels, two DC motors in the front and rear racks and two linear actuators located in the joints of the chair structure.

The linear power actuators MATRIX..3A were chosen for low cost, small size, lightweight linear power and mechanical-electrical characteristics (120W, maximum 8000 N, 5-7 mm/s, 24V, weight 4.5 kg). The linear actuators are driven by an MD22 Advanced Motion Control PWM servo amplifier.

The racks and the wheels are actuated by Maxon 148867 DC Motors with planetary gearbox (Maxon motor 203129, reduction 156:1), which were chosen with the same properties as the linear drives. (150W, 24V, 8200 rpm, weight 2.2 kg). These are driven by an Advanced Motor Control EPOS 24/5 servo amplifier.

4.3. Control system

The control system is a system composed of a main CPU, a Digital/Analog I/O board and a serial port board. The digital output board is used to control the electromagnetic solenoids. The analog input board is used to acquire sensorial data from the different sensors. The analog output board is used to command two DC motors (the two degrees of freedom of the chair) joint drivers based on the pulsewidth modulation technique. The serial port board is used to acquire sensorial data from ultrasound sensors and to command four DC motors (two for rear wheels and two for racks) joint drivers also based on the pulsewidth modulation technique.

The motor positions, linear drives and DC motors, are controlled via proportional-derivative (PD) control loops. The PWM servo amplifiers control the current to the motors and actuators, thus obtaining estimation of the torques at the motor shaft as long as the motors are not saturated. The system operates at 24V nominal voltage provided by two batteries, and a conditioning circuit that provids regulated voltages at 5V, 18V and 24V. Finally, the main CPU, with the I/O board and the serial port board, collects data from the sensors and performs the computations for implementing the various control schemes. Fig. 11 shows the control architecture of the control system.

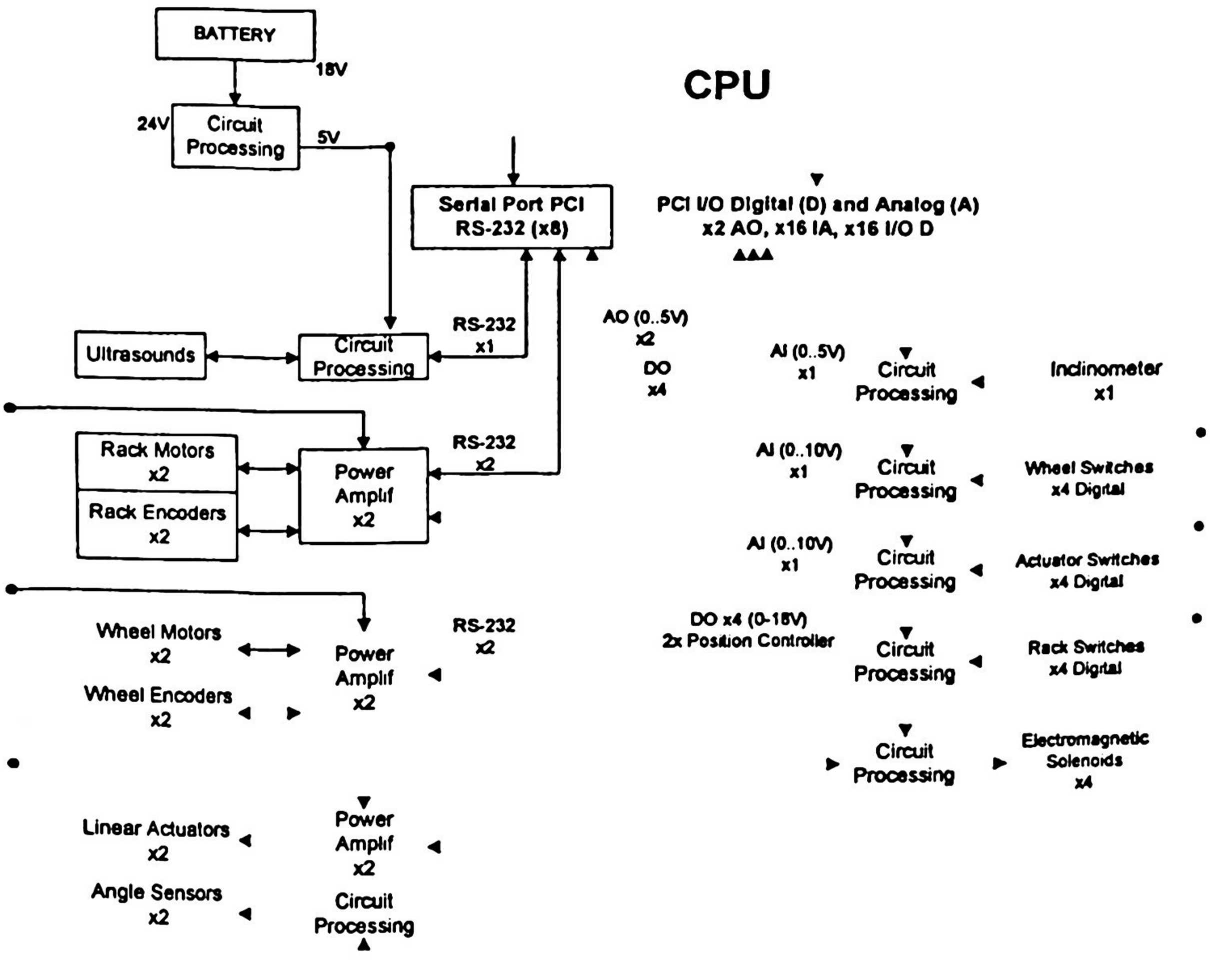

Fig. 11. Control system schematic.

4.4 Software Control

The software for operating the new prototype at this time is implemented in a Standard Microsoft Windows 2000 operating system. The user interface shows the graphical evolution of control variables and allows the user to interact with the prototype, both moving a single actuator or imposing a specific position and inclination. All this user interface has been developed with LabView 7.1. This software has been used to check the correct movements of the prototype in the climbing process and to detect the parts of the mechanism that need to be improved.

In future experiments, we will change the Pentium processor to a PC-104 board running RT-Linux environment for the control system.

5. Kinematics model of control

The most critical part of the whole control system is the subsystem that generates the real time trajectories for the actuators of the wheelchair, in such a way that this vehicle should be able to climb and descend staircases keeping the maximum possible comfort for the passenger: smooth motions and very little deviation from the vertical.

These real time trajectories are the references for the closed-loop systems (servo-controls) that control the angles of the motors (actuators) in charge of moving the several degrees of freedom of our wheelchair. This trajectory generator relies on a kinematic model that should be: a) precise enough to describe the behaviour of the mechanism, b) simple enough to be able to be computed in real time, c) flexible enough to include descriptions of all the tasks mentioned in the previous section, which include different chair configurations and different situations of contact with the environment (floor and staircases).

5.1. Direct kinematic model

The direct kinematic model provides the values of the center of mass (P_g) and the inclination of the wheelchair (γ) which are obtained from a specific value of actuator variables. When the wheelchair climbs the stair, it can present in one of four possible configurations.

In direct kinematic model we know the angles of the joints of the chair structure (θ_1 and θ_2) and depending on the configuration, the height h between the centre of the wheels, the contact point P_C between the rack and the floor, the position of the front wheels θ_3 or the instantaneous length of the stem (z) and we obtain the values of the center of mass (P_g) and the inclination of the wheelchair (γ).

5.2. Inverse kinematic model

The inverse kinematic model provides the values (angles) of the actuator variables which are needed to achieve a desired center of mass position and inclination of the wheelchair.

In inverse kinematic models, we know the center of mass position (P_g) and the inclination of the wheelchair (γ). Moreover, we also know the height difference (h) between axles (when the chair is supported on four wheels), or the relative height between the contact point of the rack and the opposite axle (when the chair is negotiating a step). With these data we obtain the angles of two joints θ_1 and θ_2, and the position of the front wheels θ_3 or the instantaneous length of the rack (z), depending on the configuration.

6. Trajectory Generation

The trajectory desired for the point P_g is designed by linking two arcs of circumference and one straight trajectory. Also, the movement must be comfortable for the passenger. This constraint implies that we cannot exceed the maximum acceleration and the maximum velocity defined, and that verticality of the seat must be maintained.

6.1. Equations of Movement

In Fig. 12, we can see the global trajectory desired for the wheelchair. And in Fig. 17, we can see the profile of velocity desired. We assume that the velocity is $V=a \cdot t$ in the interval (0, T_1), where a is the tangential acceleration. The results are:

$$x(t) = x_0+R\ \sin(at^2/(2R)) \quad (1)$$

$$y(t) = y_0+R-R\ \cos(at^2/(2R)) \quad (2)$$

$$V_x(t) = a\ t\ \cos(at^2/(2R)) \quad (3)$$

$$V_y(t) = a\ t\ \sin(at^2/(2R)) \quad (4)$$

$$a_x(t) = a\ \cos(at^2/(2R))-a^2t^2/R\ \sin(at^2/(2R)) \quad (5)$$

$$a_y(t) = a\ \sin(at^2/(2R))+a^2t^2/R\ \cos(at^2/(2R)) \quad (6)$$

If we assume that the velocity of P_g in $t=T_l$ is V_{max}, the conditions of tangencial acceleration a, curvature radius R, and time T_l to achieve V_{max} are:

$$a = a_{max}/\mathrm{sqrt}(1+(2\xi)^2) \quad (7)$$

$$R = (V_{max})^2/(2a\xi) \quad (8)$$

$$T_l = \mathrm{sqrt}(2R\xi/a) \quad (9)$$

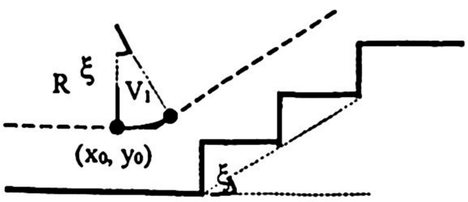

Fig. 12. Geometry of the design trajectory.

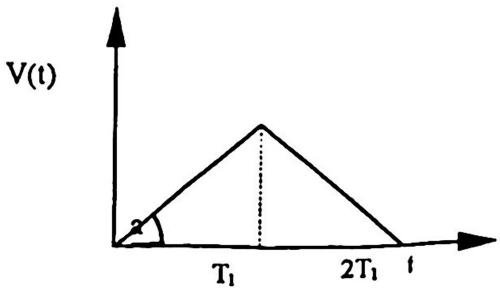

Fig. 13. Profile velocity in the part of the circumference trajectory.

In the other parts of the trajectory, the acceleration is a_{max}.

6.2 Simulation Results

This is one example of the stair climbing movement of the wheelchair. Let us have a staircase with eight steps. The dimensions of the steps are 150 mm (height) x 250 mm (width). The trajectory must be comfortable for the handicapped, this means that accelerations and velocities must be lower than the maximum acceleration of comfort and maximum velocity of comfort, and the inclination of the wheelchair must be null

($\gamma = 0$). These conditions involve that our movement will be composed of two movements (one to accelerate the wheelchair and the other to deccelerate it). The results of the simulation are (figs. 14-23):

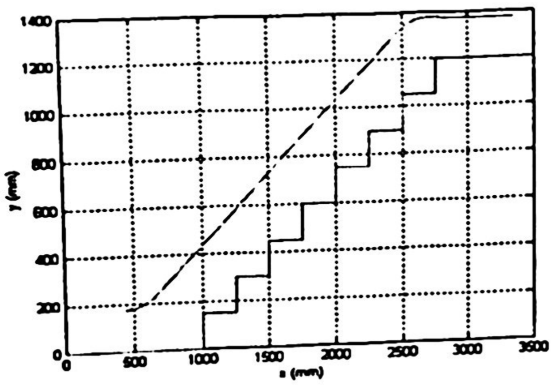

Fig. 14. Trajectory center of mass.

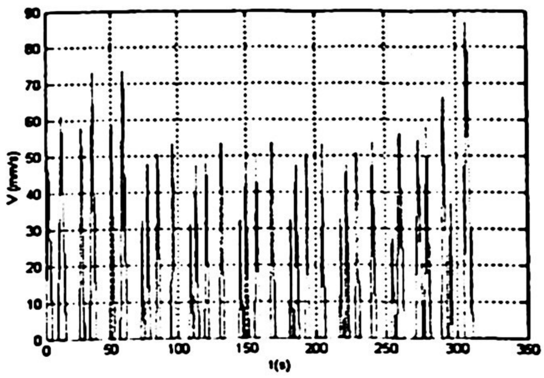

Fig. 15. Velocity center of mass.

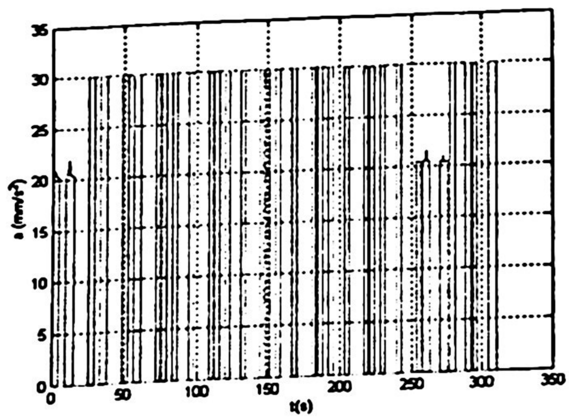

Fig. 16. Acceleration center of mass.

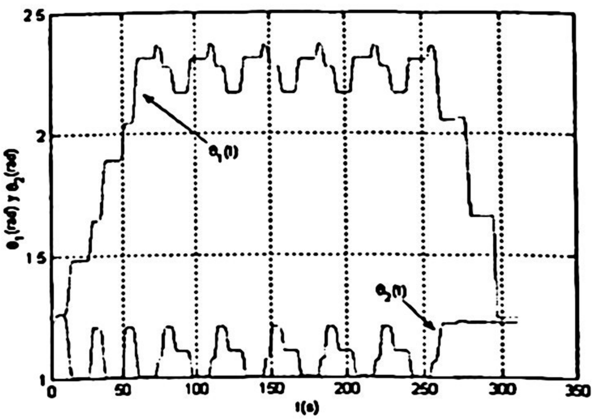

Fig. 17. Angles of joints connecting the chair structure.

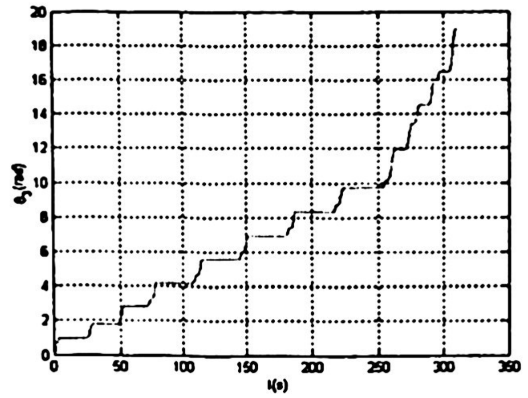

Fig. 18. Position of the rear wheels.

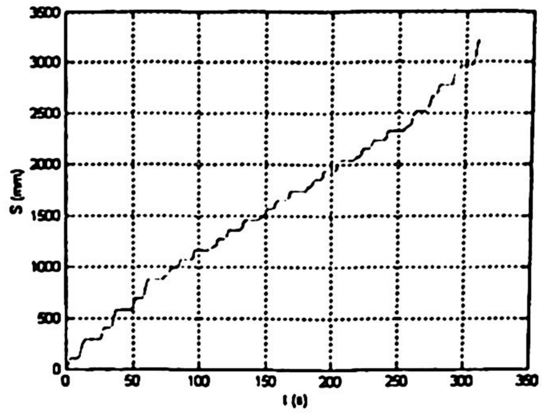

Fig. 19. Trajectory evolution.

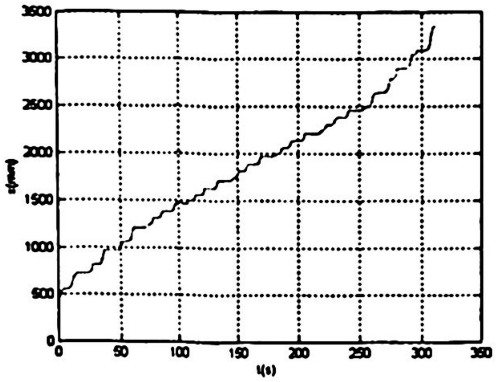

Fig. 20. Horizontal position center of mass.

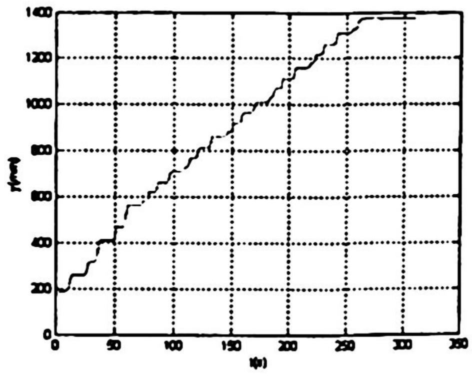

Fig. 21. Vertical position center of mass.

In the simulations, we show that the movements of all the motors are very smooth. Most of the time that the wheelchair is moving, the movement is produced with maximum comfort acceleration. However, 60% of the time needed to climb the staircase is a idle time. One of the future works pending is to design new trajectories that minimize the existence of idle time.

7. Experimental set up and prototype description

In this section, a mechanical description of the real prototype is presented to explain the advantages of the final design (autonomy, modularity and low cost), a presentation on the first experiments to calibrate the kinematic model is given next.

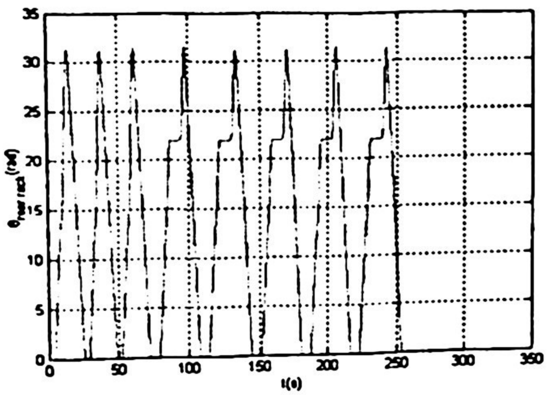

Fig. 22. Angle of rear rack.

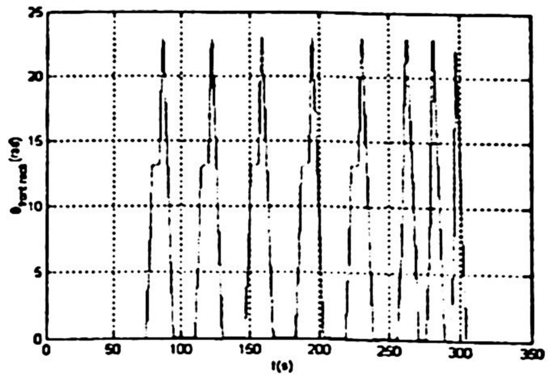

Fig. 23. Angle of front rack.

7.1 Prototype description

The prototype has been designed with the following goals. Central to the design of any mobility device is safety, but the aspect of maximizing autonomy is also very important. The structure must be both rigid and light. This was achieved using closed structures such as four bar mechanisms with a very rigid actuator driving the degree of freedom.

Another important objective was the modularity of the prototype. This implies an important cost in manufacturing and it is a direct consequence of the different approach to the problem, which has been split into two subproblems. In this way, the single step-climbing mechanism is the same for every wheel and the positioning mechanism is made up of a main structure and a front and rear structure which are pretty similar. The prototype is also designed to maximize the range of the staircases to be climbed.

Some prototype specifications are listed below:

Max. passenger weight	100 kg
Vehicle plus battery weight	30 kg + 30 kg = 60 kg
Power source	12 V, 35Ah x 2
Drive motors	24VDC (150 W x 4, 120 W x 2)
Max. prototype work environment	See Fig. 25
Max. slope allowable	45°

7.2 Experimental set-up

The first experiments that we will carry out with the prototype are the calibration model. We search for differences between the kinematic model proposed in [6] and the real prototype, and we calculate the offsets in the model. In these experiments, we carry out a motor auto-tunning to estimate the dynamic behaviour for each motor. We assume that the dynamics of the motors is negligible compared to the whole system because time response of the whole prototype is much slower than the time response of electrical motors. We simulate smooth prototype movements in all possible configurations and we collect the motions with an Optotrack system. The accuracy of the Optotrack system is approximately 0.5 mm in a work space of 2 m^3.

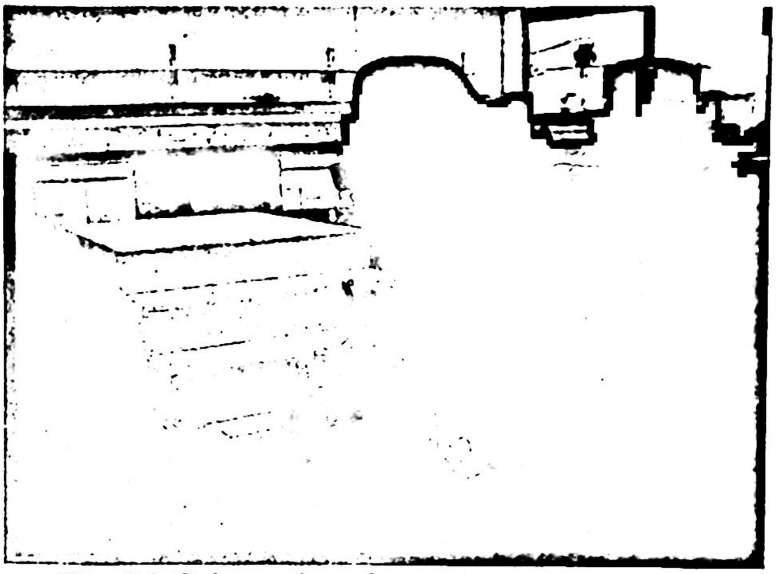

Fig. 24. Schematics of experimental prototype.

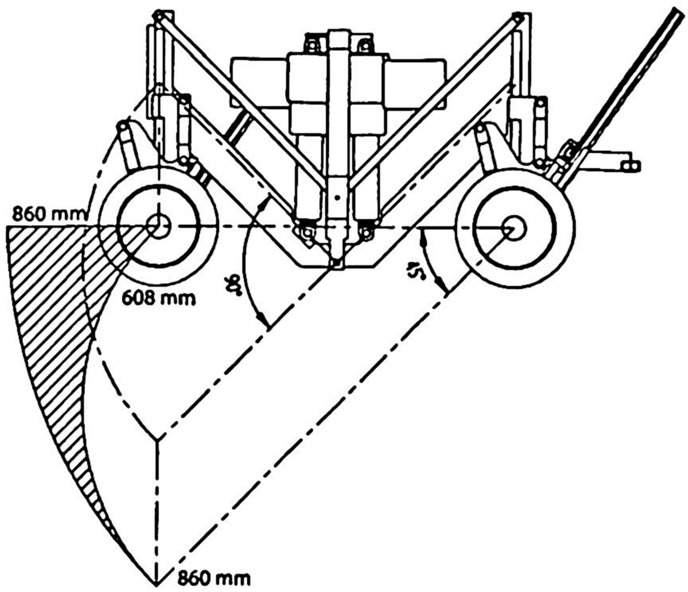

Fig. 25. Prototype work environment

The Optotrak motion analysis system is prepared with ten infrared markers which will be used to record the wheelchair trajectories. Two infrared markers are placed on the axles of rear and front wheels, two markers in each rack and four markers distributed on the chair structure. In this way, the real-time movement of the prototype will be properly recorded throughout the test course. The prototype movement must be synchronized with Optotrak systems by a switch.

8. Conclusions

A new original prototype of a staircase climbing wheelchair has been designed, its main characteristic being its stability. Moreover, its additional degrees of freedom allow motions and control strategies that take into account the comfort of the passenger (i.e. maximum acceleration and null inclination of the wheelchair). Accurate control architecture (hardware + software) is needed to operate the whole system and has been designed to be as simple as possible. Kinematic models have been developed for the different stages of motion and these models are simple enough to be used for real time control purposes (iterative calculation procedures are not necessary). The prototype has been designed keeping in mind the objectives of high safety, high modularity and low cost. In future works, we will analyze the results of calibration and we will start the dynamic model experiments to operate the whole system.

Acknowledgments

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