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Mechanical and Kinematics Design Methodology of a New Wheelchair with Additional Capabilities

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1. Introduction

Since wheelchairs appeared, only minor changes have occurred with regard to their basic design. An important change was the design of the powered wheelchairs, and it is unquestionable that they greatly improve the mobility of the handicapped. Nevertheless, architectural barriers still exist in many cities and buildings, and it is expensive and time consuming, if not impossible, to eliminate all of them. A new advance in mobility assistance came with the development of wheelchairs capable of negotiating architectural barriers. The first commercial models were based on a single-section track mechanism (SUNWA Co. Ltd). A disadvantage of these tracked systems is that the entire track is forced to rotate on the edge of the first step when initiating descent. This is a difficult and dangerous operation. An evolution of this mechanism principle has been the use of low pressure tyres for ascending and descending stairs. These systems exploiting their ability to produce high grip forces on the edge of the obstacles improving the mobility and efficiency in barrier free locomotion (Uchida et al., 1999), (Hirose et al., 2001), but the basic limitations of this design still remain.

Other designs based on wheels improve the efficiency in barrier free environments but needs additional mechanisms to overcome the architectural barriers. A commonly used solution is to group two, three or four wheels in a rolling cluster. The simplest models are little platforms to carry light wheelchairs (The Wheelchair Lift Company). A negative aspect of this solution is the necessity of an assistant. To operate the system without assistants, a more complex control system is required (Kamen et al., 1999). The problem can be solved by adding another cluster (Lawn & Ishimatzu, 2003). While the mechanical solution is quite simple, the systems are very sophisticated since it relies on dynamic control to maintain the upright position. The main disadvantages of these designs are the high actuating cluster torque, high number of wheels that must be driven and braked, difficulty to add a steering mechanism, and a dramatic increasing in weight, size, and cost.

Solutions based on legs improve the movement of the robots in highly unstructured environments (Hirose, 1984), (Kar, 2003), (Cham et al., 2002), but their low efficiency in horizontal locomotion forces us to discard legs as a way of providing mobility for the elderly or the disabled. To enhance motion capabilities wheels are incorporated. These vehicles are referred to as high-mobility robots since they combine the efficiency in

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horizontal locomotion with the versatility provided by the legs when climbing steps. As the degrees of freedom of the legs and wheels are independently actuated, these systems have the ability to control their posture. There are several robots that use this kinematics scheme (Aarnio et al., 2000), (Grand et al., 2004), (Hirose & Takeuchi, 1996). Some of them have been designed with the objective of providing mobility for disabled people (Wiesspeiner & Windischbacher, 1995), (Wellman et al., 1995). These robots demonstrate the drawback of the high number of degrees of freedom which require higher energy consumption and higher prototype mass. There are prototypes that try to overcome these problems (Siegwart et al., 2002) using six motorized wheels and a parallel mechanism to climb obstacles and surpass rough terrains.

This chapter describes a complete mechanical and kinematics design methodology of a new wheelchair with additional properties like: a) a capability of adapting to the environment overcoming special profiles characterized by obstacles with vertical slopes (discontinuities), b) a capability to move the system, in a comfortable way for the passenger, over continuous smooth profiles and c) a capability to ascend or descend staircases. It is very important to remark that these new qualities are obtained without the necessity of personal assistance.

The chapter is organized as follows. All the mechanical design methodology is described in section 2. This section includes the description of the different mechanical devices, the performance of these mechanisms in real situations and the mechanical synthesis design used to obtain a compact solution. Section 3 presents a kinematics design methodology which performs the forward and inverse kinematics over smooth profiles. Moreover, this methodology can be easily particularized to special profiles characterized by obstacles with vertical slopes (staircases). Section 4 gives a short description of the experimental prototype designed. Experimental results of the real prototype as it climbs a staircase have been developed in Section 5. Finally, Section 6 contains conclusions and Section 7 provides suggestions for future development.

2. Mechanical Design Methodology

The authors of this chapter believe that most of the previous wheelchair designs have severe drawbacks that impair their widespread use. These prototypes share the common problems of complexity, high weight and small flexibility when presented with different obstacles. To solve these difficulties, a new design strategy is developed. The first step lies in split the staircase climbing problem in two different problems: a) front and rear axle positioning to ensure the stability of the whole system and the vertical maintenance of the seat, and b) single step climbing. The second step of this innovative strategy is the use of two independent mechanisms to solve every problem.

This approach requires that the problem to overpass architectonical barriers is being decomposed in the resolution of two independent questions:

- *Climbing Mechanism*: This problem consist of overcoming a single step. The height of the step is uncertain but delimited. After step is overcome, the mechanism returns to its original position.
- *Positioning Mechanism*: This problem lies in ensure the stability on the whole system and the verticality of the seat in environments with different height axles.

Figure 1 illustrates the scheme of the system designed. The parts of the climbing mechanism are numbered with 1.X and the elements of the positioning mechanism are numbered with 2.X. The use of two decoupled mechanisms is the key feature of the mechanical design. It provides additional advantages such as simplification of the computer simulations, an easier way to develop revisions in the mechanical devices, and a faster development of the mechanical components.

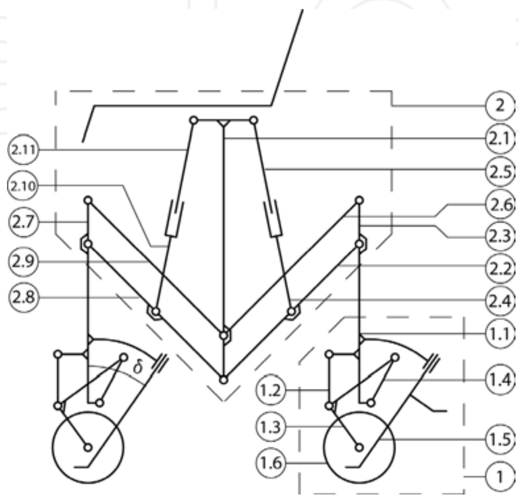

Figure 1. Prototype Scheme

2.1 Climbing Mechanism

The *climbing mechanism* (see labels 1.X in Figure 1 and Figure 2) allows to surpass a single step by every support point of the vehicle. There are two climbing mechanisms in the system, the front climbing mechanism and the rear one. This kind of mechanism must provide a way to maintain the contact between the wheel and the obstacle and to ensure the required traction in all the different configurations which compose the climbing process. Therefore, the *climbing mechanism* must fulfil the next two conditions: a) The traction force must be ensured for the trajectory without dependence on friction; b) The wheel centre trajectory must be adapted to the obstacle geometry.

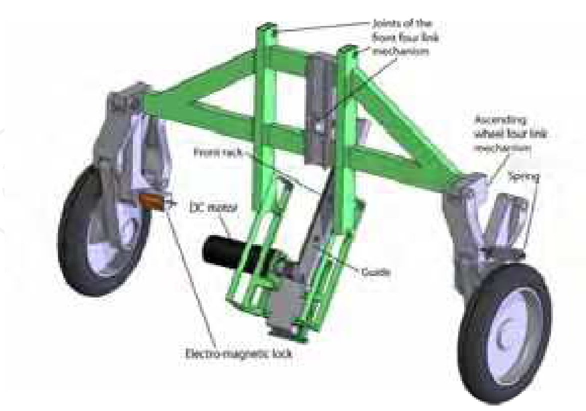

Figure 2. Climbing Mechanism Designed

The proposed climbing mechanism is composed of a frame attached to the wheelchair chassis, a four bar linkage, and a sliding support in a fixed angle δ. The four bar mechanism allows the wheel to move backward to avoid interference with the step and ensuring surface adaptation. This new degree of freedom can be cancelled with an electromagnetic lock. On the other hand, the sliding support is joined with the chassis by an actuated prismatic joint. It ensures the traction during the obstacle climbing process and provides a smooth, simple and easily controlled trajectory. The main advantage is that the climbing or descending process can begin without help when the electromagnetic lock is unlocked. A drawback is that the free barrier wheel position of the climbing mechanism can be movable. In this case, the component of the reaction force in the direction of the trajectory may push the wheel to move forward and, therefore the wheel axle have to be locked when the system moves in free barriers environments.

Figures 3 and 4 show a position sequence during step climbing and step descent. In step climbing, once the wheel is close enough to the step, the sliding support is deployed. When the sliding support touches the tread of the step, the weight is transferred from the wheel to the sliding support. The wheel mechanism is now free to move, making it possible to surpass the step. When this occurs, the wheel moves back to its original position, triggering retraction of the sliding support, and receiving weight upon the wheel bar is locked again. In step descent, the process is similar to climbing process, with the operations sorted in inverse order. In this way, once the wheel is close enough to the step, the sliding support is deployed until it reaches the thread of the step. In this moment the wheel bar is unlocked and the geometry of the four bar mechanism make the wheel move forwards to surpass the step.

The last question about the design methodology of the climbing mechanism is the mechanism synthesis. A four-bar mechanism has been proposed because of its robustness, high trajectory generation ability, light weight and compact design. The proposed four-bar mechanism can be synthesized to obtain a desired trajectory of a reference point of the coupler. This point is the wheel centre and its trajectory must be as close as possible to a straight line with a slight ascending slope δ. There are a great number of four bar mechanism configurations that fulfil with the previous requirements. To reduce the number of possible solutions, we imposed some geometrical restrictions to obtain a compact final system. Figure 5A depicts the vector analysis used in the synthesis process of the mechanism and Figure 5B illustrates the resulting mechanism.

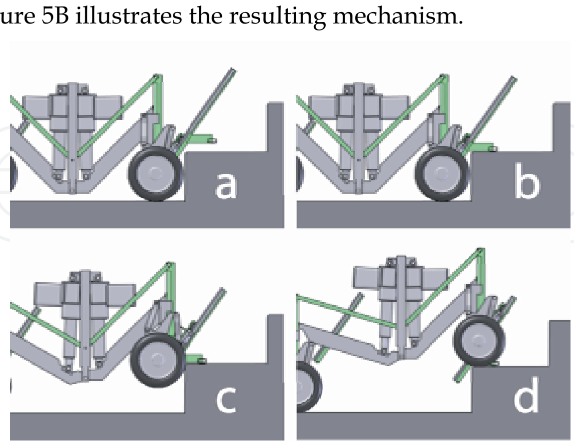

Figure 3. Step climbing process

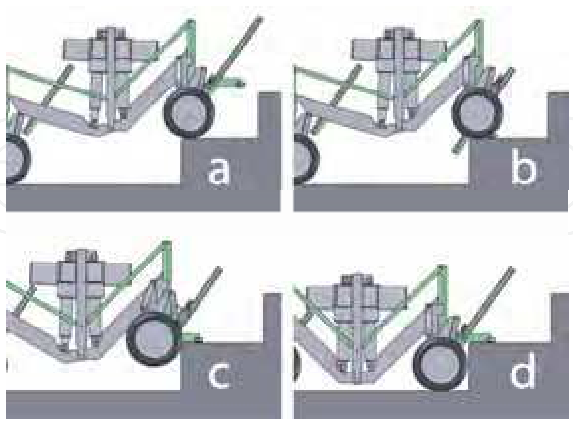

Figure 4. Step descent process

The synthesis of the mechanism has been developed to ensure that the instantaneous rotation centre of the coupler is placed in such a way the direction of the wheel centre in the initial point has the desired slope. This constraint is necessary to ensure that the mechanism has the proper behaviour in the initial point. Finally, we have to remark that the length of the path is enough to climb the most usual steps the user can face (DIN18065, 2001). With this consideration one can find the final configuration as a conventional problem of synthesis of a trajectory. Figure 6 shows the scheme of the synthesized mechanism in different instants of the climbing process. The dotted line represents the trajectory of the wheel centre.

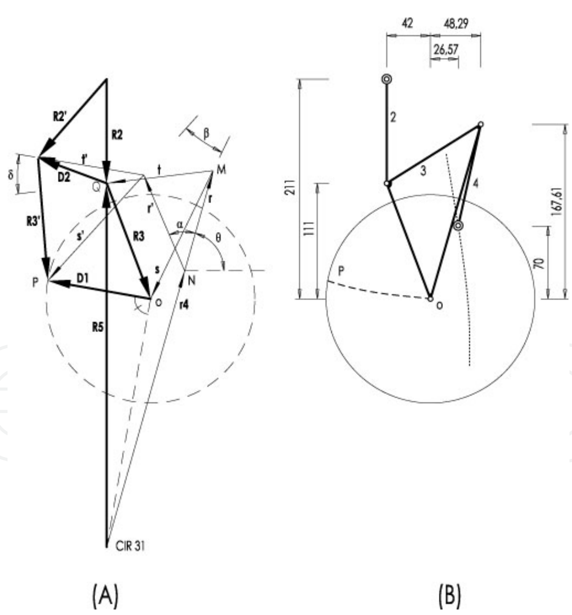

Figure 5. (A) Vector analysis used in the synthesis process of the climbing mechanism. (B) Resulting climbing mechanism

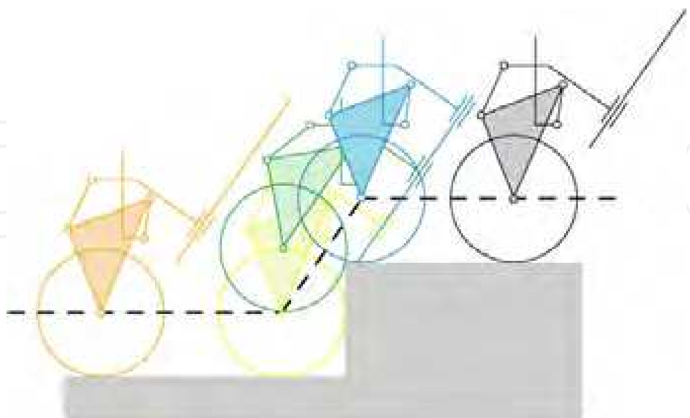

Figure 6. Trajectory of the climbing mechanism when overpass an obstacle

2.2 Positioning Mechanism

The *positioning mechanism* is the device in charge on two tasks: the positioning of both axels to maintain stability, and the accommodation of the wheel base to the stair tread. If we design a system to perform the first task only one parallelogram is needed. But the second task is necessary to perform the climb of the staircase with both axles moving in a coordinate way. Therefore, this system is designed as a parallel robot because of is highly accurate positioning and orientation. Moreover, these kind of robots offer excellent properties as high accuracy for manipulating heavy objects, high velocities and often a higher repeatability that justify their use in a large array of industrial applications. Compared to serial mechanisms, they may exhibit a much better repeatability (Merlet, 2000), but not necessarily a better accuracy, because of their large number of links and passive joints (Wang & Masory, 1993) limits their performance.

In the design of the positioning mechanism we propose a closed-loop mechanism in which the mobile platform is connected to the base by at least two serial kinematics chains. The first applications of these closed loop robots can be found in testing tire machines (Gough & Whitehall, 1962) and in the motion platform for pilot training simulators (Stewart, 1965-66). Figure 1 shows the parts of the positioning mechanism numbered with 2.X. In this mechanism, both the front and the rear axles are joined to the frame by means of four link mechanisms (labels 2.1, 2.3 and 2.7). Each four link mechanism is driven by an independent actuator (labels 2.4 and 2.10). These mechanisms are parallelogram, which means that the frames of the front and rear axles do not rotate with respect to the main frame. The overall system has two degrees of freedom which are driven by two linear actuators. The basic tasks that the positioning mechanism performs in the staircase climbing process are: a) ensuring that the weight is transferred at all times to horizontal surfaces, making it unnecessary to rely on friction to ensure safety; b) arbitrarily position both axles with respect to the frame to accommodate the overall slope allowing the implementation of many different climbing strategies. The second task of the positioning system is very important in order to ensure a comfortable staircase ascent or descent. The negative point is that the workspace is more complex.

The last question about the design methodology of the positioning mechanism is the mechanism synthesis. The condition imposed on the positioning mechanism is ensuring the accommodating process for all the staircases that are built according to (DIN18065, 2001). This standard gives the maximum and minimum width and height for the steps. Figure 7 shows the vector analysis used in the synthesis process of the positioning mechanism. In this analysis are four extreme positions for the centre of the wheel to perform the accommodating process. These positions are explained next:

N: maximum width and height. In this position the wheels are in its maximum separation and, obviously, both parallelograms will be collinear.

N′: minimum width and maximum height. This is the staircase with the maximum slope (dark gray staircase in Figure 7).

N′′: minimum width and height.

N′′′: maximum width and minimum height. This is the staircase with the minimum slope (light gray staircase in Figure 7).

These four points are the corner of a rectangle called *objective rectangle*. When one of the wheels is in contact with the upper step, if the positioning mechanism is able to place the other wheel in the four corners of the objective rectangle the accommodation process for any staircase is achievable. The design of the mechanism is an iterative process to synthesize the parallelograms. This process searches a mechanism which can reach points **N** and **N′** (in this case points **N′′** and **N′′′** can be also reached as it is shown by dashed lines in Figure 7). Vectors **r** and **s** represent the lower bars of both parallelograms when the centre of the wheel is in **N**. When the wheel goes to **N′** these bars are represented by **r′** and **s′**. Vectors **R2** and **R3** belongs to the lateral platforms and join the centres of the wheels with the joints of the parallelograms. The point **P** is the common joint of the parallelograms with the central platform.

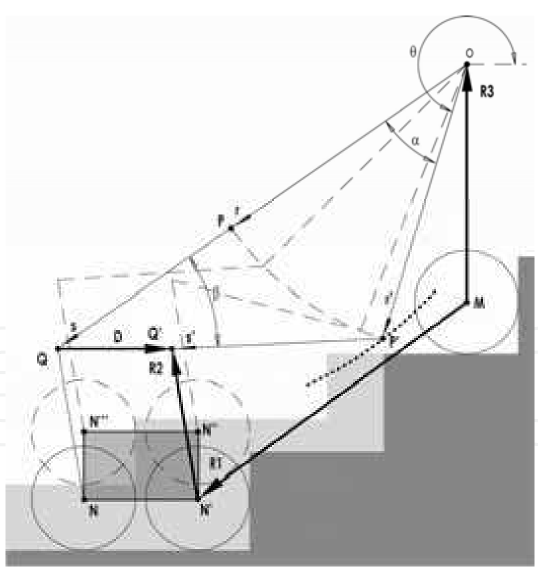

Figure 7. Vector analysis used in the synthesis process of the positioning mechanism

The first step consists of defining vectors **R2** and **R3** according to the geometrical restrictions of the wheelchair. For example, vertical component of R2 must be as shorter as possible because a large value implies a too high seat. Vector **L** will be defined as **L** = **r** + **s**, therefore **r** = c**L**, where *c* is a constant. In this way the equation of the couple of vectors **r-s** can be written as follows (Erdman & Sandor, 1997):

$$c\mathbf{L}\left(e^{j\alpha}-1\right)+(1-c)\mathbf{L}\left(e^{j\beta}-1\right)=\mathbf{D} \tag{1}$$

where **D** join points **N** and **N'**. In this equation α, β, and c are unknown variables. If β is taken as a parameter, the analytical solution for α can be obtained as:

$$\tan\alpha=\frac{\left(V_Y^2-V_X^2+1\right)\sin\beta+2V_XV_Y\cos\beta-2V_Y}{\left(V_X^2-V_Y^2+1\right)\cos\beta+2V_XV_Y\sin\beta-2V_X} \tag{2}$$

where:

$$\mathbf{V}=\frac{\mathbf{D}}{\mathbf{L}}-e^{j\beta}+1 \tag{3}$$

The geometry of the system can be easily rebuilt when α is known. Dotted line in Figure 7 represents the position of **P** for different values of parameter β. The position of **P** allows checking the suitability of the mechanism in order to avoid interferences with stairs. If a valid solution have not been found the process returns to the first step changing the initial values for **R2** and **R3**.

The final geometry obtained with the iterative process for the positioning mechanism is shown in Figure 8. The figure also shows the geometrical parameters and the workspace. It must be remarked that the wheelchair can perform the staircase climbing even though the accommodating process is not carried out. For this reason it can be reasonable to use a narrower objective rectangle in order to obtain a more compact wheelchair. This rectangle is chosen in such a way the most usual staircases are included.

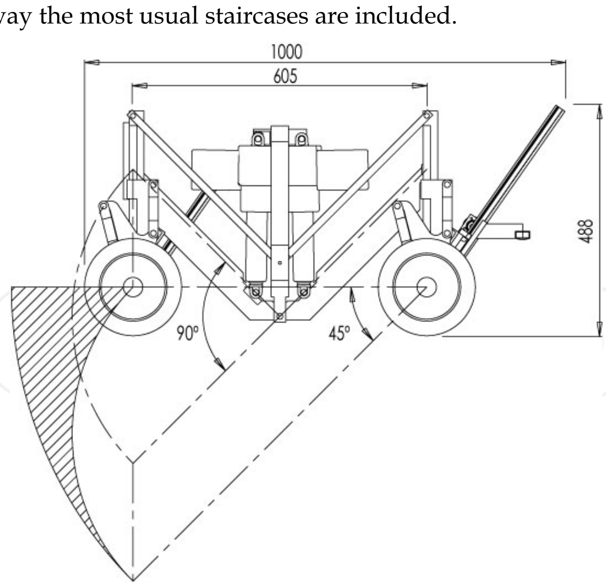

Figure 8. Geometrical parameters and work environment

3. Kinematics Design Methodology

Regarding the mechanical structure, modularity was the key factor in the design methodology of the system. The wheelchair driven degrees of freedom are split into two subcategories: the fist concerns the locomotion itself (traction and ascent step) and the second concerns the posture (verticality of the chair frame). Both categories will be treated together in the kinematic model as they are coupled, but the appropriate mechanical design simplifies the control.

The determination of a kinematic model becomes a critical part of the whole system because it has the responsibility of generating the real time trajectories for the actuators of the wheelchair, in such a way that this vehicle should be able to climb and desdent staircases maintaining maximum possible comfort for the passenger: smooth motions and very small deviations from the vertical. These real time trajectories are the references for the closed-loop systems (servocontrols) 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 behavior of the mechanism; (b) simple enough for computation 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).

Based on the modularity of the system, we proceed to develop all the kinematics methodology of the wheelchair. On the one hand, we define as *forward kinematic model* (FKM) the algorithm which provides the position of the center of mass ($\mathbf{P}_g$) and the inclination of the wheelchair (γ) with regard to specific values of actuator variables. On the other hand, we define as *inverse kinematic model* (IKM) the algorithm which gives the values (angles) of the actuator variables needed to achieve a desired centre of mass position and inclination of the wheelchair. We perform the kinematics methodology over smooth continuous profiles because is very easy to particularize on profiles composed by flat floor and staircase profiles. In these special profiles characterized by obstacles with vertical slopes (discontinuities), both forward and inverse kinematics models allow analytical solutions and iterative calculation procedures are not needed.

Finally, we coment that all the kinematics design methodology presented in this section is based on complex notation: horizontal variable is the real component and vertical variable is the imaginary component (where j is the imaginary number). This notation facilitates the adquisition of the kinematic models in the prototype because we have found that expressions of rotations are simplified leading to more compact equations. Next, we will use operators *Re(z)* and *Im(z)* as the real and imaginary components respectively of the complex number **z**, and $\angle\mathbf{z}$ and $|z|$ will mean the phase and the complex modulus of the elements of **z**.

3.1 Forward kinematics design methodology of the wheelchair prototype over smooth profiles

In this section we present the kinematic methodology to obtain the forward kinematics model of the wheelchair over smooth profiles and the resulting expressions. Figure 9 illustrates the prototype scheme developed and its main parameters. We assume a smooth generic profile $\hat{\mathbf{f}}(s)$. We can obtain the trajectory of the centre of the wheels $\mathbf{f}(\theta)$ from a generic floor profile with the next equation:

$$f(\theta) = \hat{f}(R\theta) + \left(\frac{\partial\,\mathrm{Im}\left[\hat{f}\right]}{\partial\,\mathrm{Re}\left[\hat{f}\right]} \right) e^{j\frac{\pi}{2}} R = \hat{f}(R\theta) + \left(\frac{\frac{\partial\,\mathrm{Im}[\hat{f}]}{\partial s}}{\frac{\partial\,\mathrm{Re}[\hat{f}]}{\partial s}} \right) e^{j\frac{\pi}{2}} R \tag{4}$$

being R the radius of the wheel and s the trajectory.
The *forward kinematics model* (FKM) provides the values for the centre of mass and the inclination of the wheelchair, which are obtained from specific values of actuator variables that govern the movement of the wheelchair prototype.

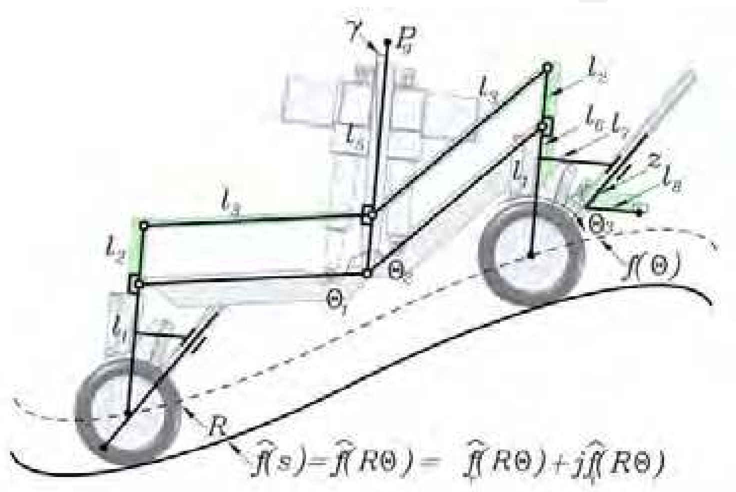

Figure 9. Wheelchair kinematics diagram

In the case of wheelchair movements in smooth profiles, we know the angles of the joints of the chair structure (θ_1 and θ_2) and the angle position of the rear wheels (θ_3) and the profile trajectory of the wheel axles ($\mathbf{f}(\theta)$). With these data we obtain the centre of mass position ($\mathbf{P}_g$) and the inclination of the wheelchair (γ).
The FKM methodology starts on the obtention of the relation between the wheel axles and the configuration of the chair structure using complex notation (Erdman & Sandor, 1997). This notation clarify that the vector which joint the wheel axles only depends on the joint angles of the chair structure (θ_1 and θ_2) and the inclination of the wheelchair (γ). The expression is illustrated next:

$$f(\theta_3) - f(\theta_4) = \left[l_3\, e^{j\left(\theta_1 - \frac{\pi}{2}\right)} + l_3\, e^{j\left(\frac{\pi}{2} - \theta_2\right)} \right] e^{j\gamma} \tag{5}$$

where $\mathbf{f}(\theta_3)$ and $\mathbf{f}(\theta_4)$ are the positions of the rear and front axles respectively.
Next, we need to obtain the position of the front axles ($\mathbf{f}(\theta_4)$). This unknown parameter results by solving the module equation of expression (5). The equations is depicted now:

$$\left| f(\theta_3) - f(\theta_4) \right| = \left| l_3\, e^{j\left(\theta_1 - \frac{\pi}{2}\right)} + l_3\, e^{j\left(\frac{\pi}{2} - \theta_2\right)} \right| \quad \Rightarrow \quad f(\theta_4) \tag{6}$$

Furthermore we have to obtain the inclination of the wheelchair (γ) by solving the phase equation of expression (5). The resulting equation in showed next:

$$\gamma = \angle[f(\theta_3) - f(\theta_4)] - \angle\left[l_3\, e^{j\left(\theta_1 - \frac{\pi}{2}\right)} + l_3\, e^{j\left(\frac{\pi}{2} - \theta_2\right)}\right] \tag{7}$$

Finally, the centre of mass position ($\mathbf{P}_g$) is obtained by using one of the next expressions:

$$P_g = f(\theta_4) + (l_1 + l_5)e^{j\left(\frac{\pi}{2} + \gamma\right)} + l_3\, e^{j\left(\theta_1 - \frac{\pi}{2} + \gamma\right)} \tag{8}$$

$$P_g = f(\theta_3) + (l_1 + l_5)e^{j\left(\frac{\pi}{2} + \gamma\right)} + l_3\, e^{j\left(-\theta_2 - \frac{\pi}{2} + \gamma\right)} \tag{9}$$

3.2 Inverse kinematics design methodology of the wheelchair prototype over smooth profiles

The *inverse kinematics model* (IKM) provides the values (angles) of the actuator variables needed to achieve a desired centre of mass position and inclination of the wheelchair. In the case of wheelchair movements in smooth profiles, we know the centre of mass position ($\mathbf{P}_g$), the inclination of the wheelchair (γ) and the profile trajectory of the wheel axles ($\mathbf{f}(\theta)$). With these data we obtain the angles of the joints of the chair structure (θ_1 and θ_2) and the positions of the rear and front wheels ($\mathbf{f}(\theta_3)$ and $\mathbf{f}(\theta_4)$ respectively).

The IKM methodology starts on the treatment of equation (8). After some calculations, we obtain the next expresion:

$$\left[P_g - f(\theta_4) - j(l_1 + l_5)e^{j\gamma}\right]e^{j\frac{\pi}{2}} = l_3\, e^{j(\theta_1 + \gamma)} \tag{10}$$

The obtention of the unknown parameters $\mathbf{f}(\theta_4)$ and θ_1 are obtained when expression (10) is split in modulus and phase equations. The results are showed next:

$$\left|P_g - f(\theta_4) - j(l_1 + l_5)e^{j\gamma}\right| = l_3 \quad \Rightarrow \quad f(\theta_4) \tag{11}$$

$$\theta_1 = \frac{\pi}{2} - \gamma - \angle\left[P_g - f(\theta_4) - j(l_1 + l_5)e^{j\gamma}\right] \tag{12}$$

Then making the same procedure in expression (9) we obtain the next expression:

$$\left[P_g - f(\theta_3) - j(l_1 + l_5)e^{j\gamma}\right]e^{j\frac{\pi}{2}} = l_3\, e^{j(\gamma - \theta_2)} \tag{13}$$

The obtention of the unknown parameters $\mathbf{f}(\theta_3)$ and θ_1 are obtained when expression (10) is split in modules and phase equations. The results are showed next:

$$\left|P_g - f(\theta_3) - j(l_1 + l_5)e^{j\gamma}\right| = l_3 \quad \Rightarrow \quad f(\theta_3) \tag{14}$$

$$\theta_2 = \gamma - \frac{\pi}{2} - \angle\left[P_g - f(\theta_3) - j(l_1 + l_5)e^{j\gamma}\right] \tag{15}$$

Finally, this design methodology can be particularized on special profiles characterized by obstacles with vertical slopes (discontinuities). The advantage of these special profiles is that DKM and IKM allow analytical solutions (iterative calculations are not needed) and this methodology has to be applied in all the possible wheelchair configurations that can appear when the wheelchair climbs stairs. All this particular methodology has been developed in (Morales et al., 2006a).

4. Prototype Description

The wheelchair prototype which has been manufactured is presented in figures 10 and 11. Some prototype specifications are listed in table 1. Moreover, the main advantages of the prototype are detailed now:

- Splitting the stair ascent/descent problem into two subproblems. Each subproblem is solved by a different mechanical device.
- High load capacity. The wheelchair has been designed to carry persons up 120 kg weight.
- Light and rigid structure was achieved using closed structures such as four-bar mechanisms with very rigid actuators driving the degrees of freedom.
- High modularity. This implies an important cost reduction.
- High safety. The mechanisms have been designed to enforce the mechanical stability while the wheelchair is on the staircase. The weight is transferred at all times to horizontal surfaces (the tread), making unnecessary to rely on friction to ensure safety.
- Environment adaptation. The prototype has been designed to maximize the range of staircases to be climbed. This was achieved by division of the device that negotiates with the step and the rest of the mechanical devices.
- Compact design. This mechanism fulfils all the regulations of standard wheelchairs.

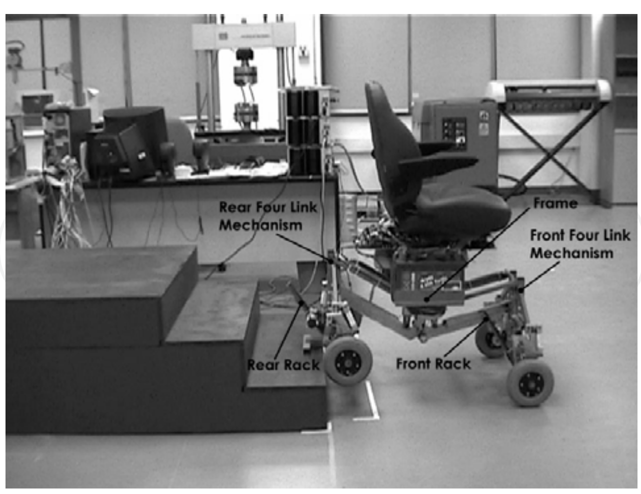

Figure 10. Prototype designed

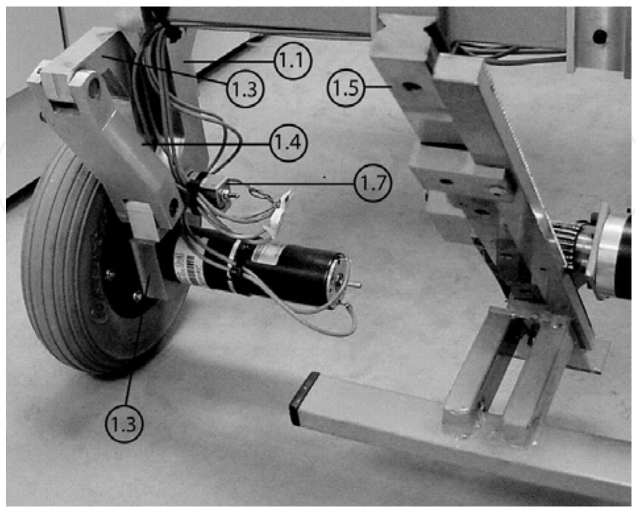

Figure 11. Details of the Climbing Mechanism

Max. passenger weight	100 kg
Vehicle plus battery weight	40 kg + 50 kg = 90 kg
Power source (battery)	12 V, 56Ah x 2
Drive motors	24 VDC (150 W x 4, 120 W x 2)
Operating range (time) Barrier free operation Stair operation	 6.4 h 3.7 h
Stair-climb speed (max.)	3 steps per min
Speed on the flat (max.)	2 Km/h
Max. height step	215 mm
Max. slope allowable	45º

Table 1. Prototype specifications

5. Experimental results

In this section we validate the relationship between the mechanical and kinematics methodology for the wheelchair prototype. We study the behaviour of the prototype as it climbs a staircase composed by two steps having step dimensions 180 mm (height) and 300 mm (width). The movements of the wheelchair on the staircase have to satisfy some conditions. The first condition is the maintenance of the verticality of the seat and the accurate tracking of the trajectory designed for the centre of mass, and the second condition is that these trajectories designed for the centre of mass must be comfortable for the passenger. This last constraint implies that the movement of the chair frame will be composed by two stages (one of them to accelerate the wheelchair and the other to decelerate it). Figure 12 shows the velocity profile of the centre of mass of the prototype in the experiment.

In the experiment, we generate control signals for the actuators in order to drive the wheelchair in an open loop fashion. Previous to the test, we have estimated 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. On the other hand, the accelerations of the whole system in the climbing/descending phases are very small in order to guarantee passenger comfort. This implies that inertial forces are very small in comparison with gravity forces.

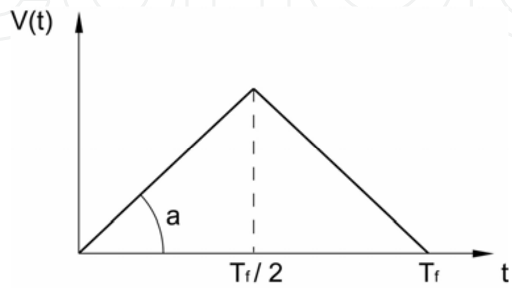

Figure 12. Profile Velocity Defined

All the information about the movement of the chair was collected using the commercial system Optotrack. This system is made by three infrared cameras which are able to obtain the location and the measure (6D) of several infrared markers. These markers are fixed in strategic points of the robotic prototype or in mobile devices whose trajectories need to be registered. In our experiment, the Optotrack motion analysis system was prepared with two infrared markers, which were used to record the wheelchair trajectories. One infrared marker was placed at the centre of mass of the wheelchair and the other one on a horizontal surface to measure the verticality deviation of the seat. Also, we use the internal hardware of the prototype. We need information about the encoders of the rear wheels and the racks, the sensors that measure the angles of the joints of the structure and the inclination of the seat. In this way, the real-time movement of the prototype was properly recorded throughout the test. An important question is the synchronization of all the data collected about the prototype movement. This problem has been solved using a trigger signal.

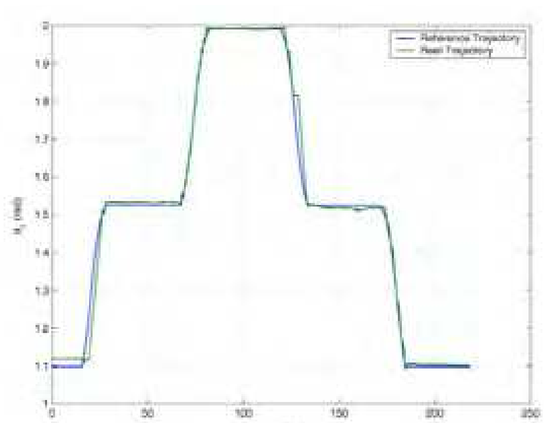

Figure 13. Front join angle evolution (θ_1) connected to the chair structure

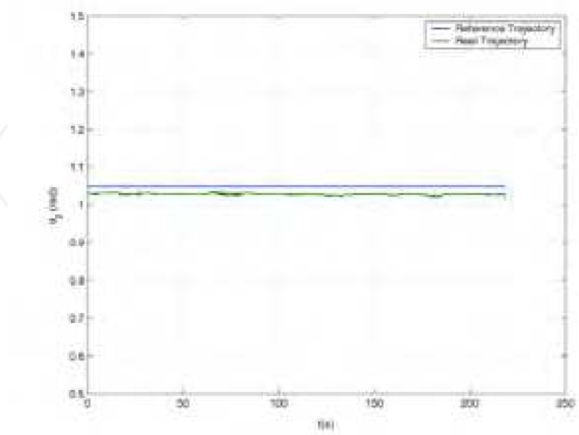

Figure 14. Rear join angle evolution (θ_2) connected to the chair structure

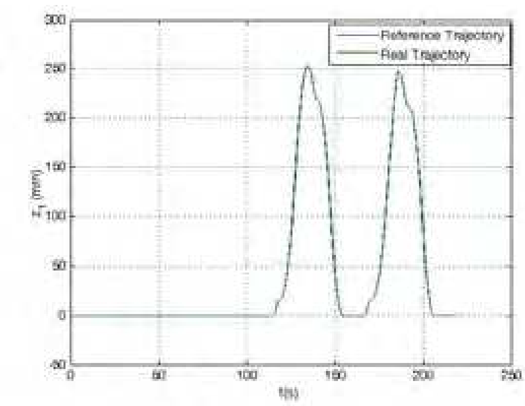

Figure 15. Evolution of the front climbing mechanism (z_1)

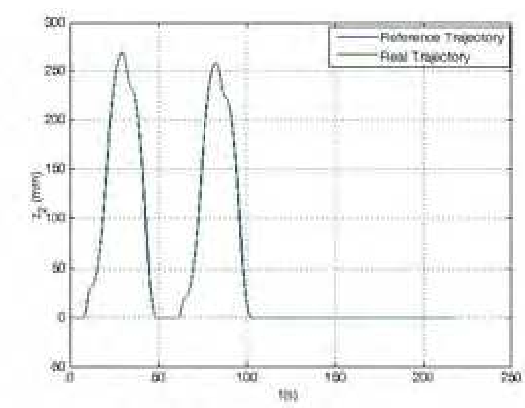

Figure 16. Evolution of the rear climbing mechanism (z_2)

Figures 13 and 14 show the reference and experimental trajectories of the angles of joints connecting the chair structure (positioning mechanism). Figure 13 shows the reference and experimental trajectories of the front joint of the chair structure. Figure 14 shows that the second actuator (responsible for angle θ_2) remains constant throughout the trajectory. Both figures demonstrate that all the responsibility of the climbing process and the maintenance of the verticality of the chair is supported by the linear actuator connected to the chair structure in charge of the evolution of θ_1. This result implies that the election of an appropriate climbing strategy (Morales et al., 2006b) allows climbing or descending staircases maintaining the passenger comfort and the verticality of the chair. This is done by moving only a subset of all the degrees of freedom available in the robotic wheelchair (the rest of the actuated degrees of freedom are kept constant), decreasing the power consumption.

Figures 15 and 16 illustrate the trajectories of the front and rear climbing mechanisms. In these figures we can see the deployment movement and the backward movement of each climbing mechanism when they confront the obstacles in an individual way.

Figure 17 depicts the reference and the experimental trajectories of the centre of mass when the wheelchair climbs the staircase. The agreement between the simulation and the experimental results is good. The small differences between theoretical and experimental results are due to the geometry of the robotic prototype does not exactly match the design goals because of manufacturing or assembly defects. Furthermore, figure 18 depicts the evolution of the wheelchair inclination. In this figure the results obtained by the Optotrack system and the measurements obtained with the inclinometer are plotted.

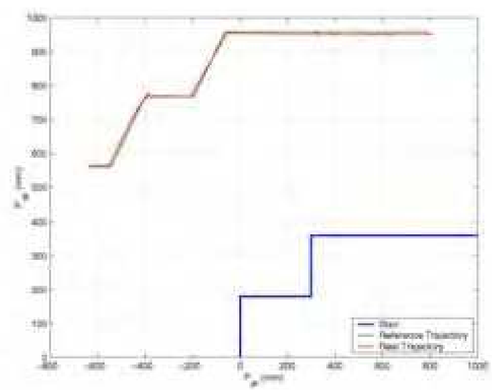

Figure 17. Trajectory of the centre of mass

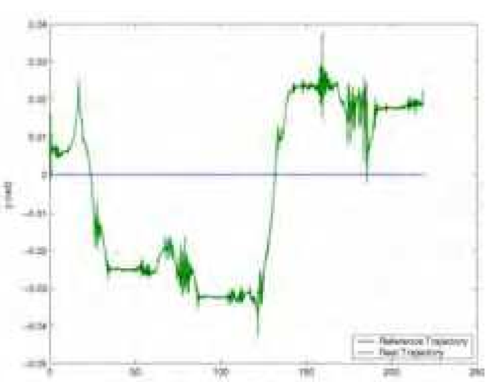

Figure 18. Evolution of the wheelchair inclination

These data, show that both measures are similar and the inclination is nearly null. Verticality throughout the trajectory has been approximately maintained using open loop control. Finally, a visual climbing process sequence is illustrated in figure 19. In this figure we can see the evolution of the wheelchair on the stair and the maintenance of the verticality of the seat during all the experiment.

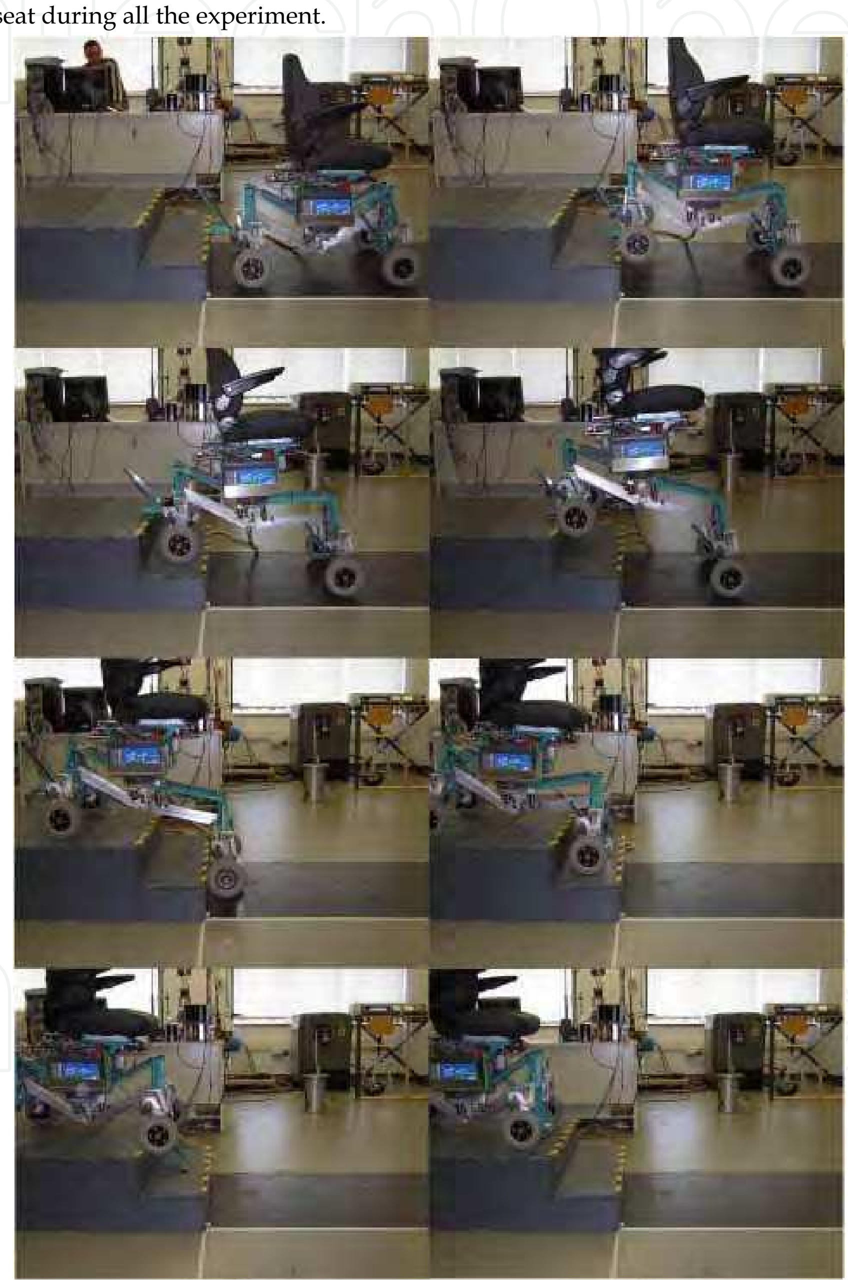

Figure 19. Climbing process sequence

5. Conclusions

A new approach has been presented for designing and building a climbing-wheelchair. Its main features are: a) automatic adaptation to steps with different heights, b) easy maintenance of the verticality of the wheelchair, c) the climbing of stairs requires less effort from the actuators (only a subset of the actuated degrees of freedom is needed when the trajectory slope of the chair frame is the same as the slope of the racks or the slope of the wheels, depending on the configuration), d) weight and energy consumption are reduced and e) wheelchair stability is guaranteed during every moment because its weight is always transferred to horizontal surfaces and the support polygon is always greater than or equal to the support polygon of the conventional powered wheelchairs.

The mechanical design methodology decomposes the original mechanical problem into two different subproblems which have been implemented with separate mechanical devices. On the one hand the climbing mechanism solves the problem to overcome a single step and on the other hand, the positioning mechanism ensures the stability and the verticality of the seat in environments with different height axles. Then, the synthesis process depicts the final dimensions of both mechanical devices. The final solution found has some advantages: very high payload capacity, light weight and low cost.

The kinematics design methodology allows full motion of the degrees of freedom of the whole system, and it has been adapted to continuous smooth profiles and profiles composed of flat floor and staircases (this profile admits analytical solutions). The inverse kinematics model of our wheelchair prototype makes it possible to determine the real time trajectories for the articulated degrees of freedom of the wheelchair. This is important since a comfortable motion of the wheelchair requires an individual motion of the degrees of freedom in order to maintain a desired motion of the whole system.

The kinematics model and the climbing strategies have been applied together to the wheelchair prototype to illustrate the good environment adaptation of our design as it moves in a staircase composed by two steps while the verticality of the seat and the trajectory of the centre of mass are maintained. All the experiments have been prepared in such a way the passenger comfort has to be guaranteed. The control trajectory is easier, as it relies basically on the motion of only one of the actuators which compose the positioning system (responsible for angle θ_1) while the second actuator (responsible for angle θ_2) remains constant throughout the trajectory. Moreover, the planned trajectories are consistent and agree with the experimental results. The reported experimental results show small deviations from the verticality, and demonstrate that our mechanical design allows our chair to climb stairs with the proposed open loop control strategy, with minimum sensors requirements, and guaranteeing the stability and the comfort of the passenger.

6. Future work

The reported experimental results show small differences between simulated and real trajectories which validate the good relationship between the mechanical and kinematics methodologies proposed. These results show some small differences between simulated and experimental trajectories that will be reduced in our next future work by a) carrying out a calibration procedure of the mechanism, and b) by implementing a closed loop control system that uses feedback of the inclinometer measurements and of several ultrasound sensors that will provide with the relative positions between the steps and the wheels. This will allow faster movements while maintaining the comfort and security margins for the passenger.

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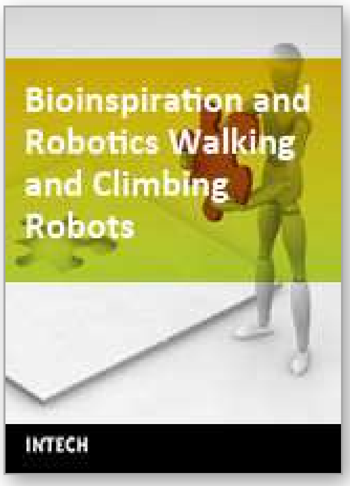

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Nature has always been a source of inspiration and ideas for the robotics community. New solutions and technologies are required and hence this book is coming out to address and deal with the main challenges facing walking and climbing robots, and contributes with innovative solutions, designs, technologies and techniques. This book reports on the state of the art research and development findings and results. The content of the book has been structured into 5 technical research sections with total of 30 chapters written by well recognized researchers worldwide.