Control architecture for a novel Leg-Based Stair-Climbing Wheelchair

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Abstract— **Based on a recently proposed leg-based stair-climbing wheelchair, this work presents the control architecture for this mechanism. The objective of this work is to propose a step by step control methodology, which can define the positions of the wheels to climb up/down stairs. This will simplify the control of the seventeen actuators involved in climbing up and down tasks. The strategy proposed in this work makes the system robust to sensor uncertainties and small errors in the mechanical parameters, making the structure safer. This control architecture facilitates the practical implementation of the kinematic control. In addition, this strategy is also useful to optimize the configuration of the mechanism.**

I. INTRODUCTION

It is well known that there are several stair-climbing assisting mechanisms for the disabled people, see for example the work [1]. Research on chair-type mechanisms capable of climbing stairs is a very active research topic nowadays. This mechanism can be classified into (see Table I in [2]): i) track-based stair-climbing mechanism, ii) wheel cluster–based stair-climbing mechanism, iii) leg-based stair-climbing mechanism and iv) hybrid stair-climbing mechanism.

Recently, in [3], a novel leg-based stair-climbing mechanism was presented. This mechanism, which is based on the patent [4], introduces some modifications, such as a novel configuration or the linear actuators. Thus, the first prototype developed and built in [3] increases the flexibility of the mechanism, allowing the wheelchair to climb up and down without changing the orientation of the chair and guaranteeing the horizontal position of the user. This first prototype presents some advantages with respect to other leg-based stair-climbing mechanisms. Thus, the horizontal position of the user can be guaranteed with a relative low-stroke in the linear actuators, which is one of the problems of the solution proposed in [5]. Besides this, it is not necessary a relative displacement among the four frame legs, which is the main problem of [6].

One of the main problems of these climbing mechanisms is the control of the actuators in order to generate safety trajectories. In addition, the control of the actuators and the strategy, which is used to climb the obstacles, are necessary in order to optimize the mechanism geometry. Some previous works have analysed variables, such as the area, the velocity, the ergonomic and/or the adaptability to different obstacles. For example, the hybrid stair-climbing mechanism presented in [7] was optimized and controlled in [7] and [8]. In [9] and [10], the Trajectory Generation is proposed in order to improve the stair-climbing time and the user's comfort and includes the most important constraints inherent to the system behaviour, such as the geometry of the architectural barrier, the re-configurable nature of the discontinuous states, state-transition diagrams, comfort restrictions and physical limitations regarding the actuators, speed and acceleration.

The leg-based stair-climbing mechanisms, such as the one defined in [3] and [4], present the problem of controlling the linear actuators. The amount of linear actuators, which must be synchronized, is one of the main limitation when these mechanisms must be controlled. Thus, it is necessary a control architecture (high-level planning), which simplifies the practical implementation of the actuators control and increase the safety of the mechanism. The objective of this work is to define the positions of the wheels to climb up/down stairs. This will be used to generate the trajectories of the electrical actuators, which considered the kinematic equations and restrictions defined in [3]. This will be useful to implement the low-level control in practice and to optimize the mechanism in future works.

The work presented starts with the definition of the prototype. In this section, the direct and inverse kinematics equations are defined. Then, the control architecture is defined. The work continues with an application example tested with a simulator created by us being programmed with python. In this section, some video links are included to illustrate how the control architecture works. The work ends with some conclusions and future works.

II. MECHANICAL DESIGN

Reference [3] proposed a new approach to the leg-based stair-climbing mechanisms. This mechanism can climb up and climb down the less favourable stairway according to [11] (see Figure 1). In addition, the proposed design can drive over uneven terrain such as cobblestones and adjust the height of the chair, which can help the user in different scenarios, such as tables with different heights or hold conversations with other people who are standing up.

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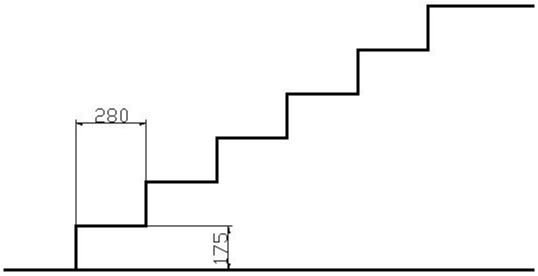

Fig. 1. Most unfavourable stairway according to [11].

A. Wheelchair mechanism description

Figure 2 shows a picture of the first scaled prototype proposed in [3]. This prototype is used to generate the trajectories of the linear actuators. This wheelchair has 17 electrical motors. Eight of these motors are used for the horizontal displacement of the wheelchair. The rest of the electrical motors are connected to linear actuators. These linear actuators (eight of them) can be used to (see Figure 3):

- Change the height of one actuator. This is used to control the position of an individual wheel ($L_1 - L_4$ in Figure 3).
- Change the height of the whole wheelchair (L_1, L_2, L_3 or L_4 in Figure 3).
- Change the inclination of the wheelchair. This task must be coordinated with $L_1 - L_4$ and $L9$ (see Figure 3)).

Fig. 2. First prototype proposed in [3].

The prototype shown in Figures 2 and 3 is a modification of the model proposed in [4]. The prototype keeps the passive mechanism defined by the points A, B and C as reference [4] introduced. However, this modification proposed in [3] changes the position of the linear actuator L_9, keeping the horizontal position if a step (or any obstacle) is climbed up and down without a change in the orientation of the mechanism (see Figure 3). Note that the distance f (segment AC) is constant and the segment AB is horizontal if the actuators L_1, L_2, L_3 and L_4 are keep vertical. In figure 3, the rest of mechanical parameters are: a, b, c, d and the radius of the wheels (r_1, r_2, r_3 and r_4).

B. Direct kinematic model

The direct kinematic model can be deduced from Figure 4. This model relates the Cartesian coordinates of wheels 2, 3 and 4 with respect to the first wheel.

As it was mentioned above, the linear actuators L_1-L_4 of the one side and the actuators L_5-L_8 of the other side must be kept vertical in order to guarantee the horizontal position of the chair, as it can be seen in the Figure 3. Thus, the rectangle of the structure must be changed into a rhomboid with an angle equal to β in order to guarantee this restriction. In addition, the angle α, which depends on β, is needed to obtain the relationship between horizontal and vertical relative position between the centres of the wheels.

According to Figure 4, the angles α and β are related as follows:

$$\alpha = \beta - 90 \tag{1}$$

where β is calculated as follows:

$$\beta = \cos^{-1}\left(\frac{d^2 + L_H^2 - L_9^2}{2 \cdot L_H \cdot d}\right) \tag{2}$$

where L_H is equal to $a+b+c$. The coordinates of the centre of each wheel, which is related with respect to the wheel 1, is defined into Equations (3), (4) and (5) as follows:

$$\begin{aligned} x_2 &= a \cdot \cos\alpha \\ y_2 &= a \cdot \sin\alpha + L_1 - L_2 \end{aligned} \tag{3}$$

$$\begin{aligned} x_3 &= (a+b) \cdot \cos\alpha \\ y_3 &= (a+b) \cdot \sin\alpha + L_1 - L_3 \end{aligned} \tag{4}$$

$$\begin{aligned} x_4 &= L_H \cdot \cos\alpha \\ y_4 &= L_H \cdot \sin\alpha + L_1 - L_4 \end{aligned} \tag{5}$$

Note that the Equations (3), (4) and (5) are valid for actuators L_6, L_7 and L_8, respectively, being the reference the wheel 5. Thus, if the objective is to climb a stair, the following restriction must be achieved:

$$L_1 = L_5 \qquad L_2 = L_6 \qquad L_3 = L_7 \qquad L_4 = L_8 \tag{6}$$

C. Inverse Kinematic model

The inverse kinematic model proposed in this work consists in defining firstly an angle α suitable for climbing the stairs. This angle can be obtained by implementing a feedback with the output of a gyroscope placed on the structure. Then, the value of β is calculated from Equation (1) as $\beta = \alpha + 90$. Therefore, the length of the diagonal (L_9) is obtained as follows:

$$L_9 = \sqrt{d^2 + L_H^2 - 2 \cdot L_H \cdot d \cdot \cos\beta} \tag{7}$$

Now, to calculate the value of L_2 (L_6), L_3 (L_7) and L_4 (L_8), it is necessary to know the value of L_1 (L_5) and the coordinates y_2 (y_6), y_3 (y_7), y_4 (y_8). The Equations to use are the following:

$$L_2 = a \cdot \sin\alpha + L_1 - y_2 \tag{8}$$

$$L_3 = (a+b) \cdot \sin\alpha + L_1 - y_3 \tag{9}$$

$$L_4 = L_H \cdot \sin\alpha + L_1 - y_4 \tag{10}$$

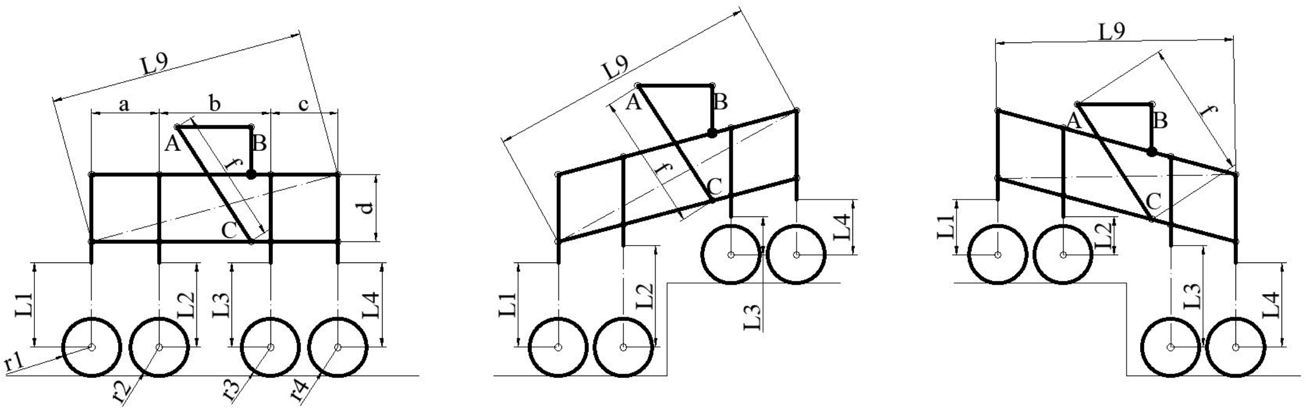

Fig. 3. Working principle. It can be seen that the user is always kept horizontal when the wheelchair is horizontal, is climbing up or climbing down an obstacle

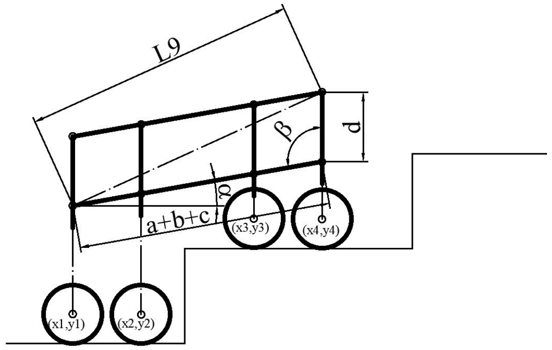

Fig. 4. Kinematic parameters used in the direct and inverse kinematic models.

D. Kinematic constraints on the leg-mechanism

The parameters a, b, c, d and the radius of the wheels depends of the step stair parameters, which are the riser and the tread. Note that in Figure 1 the riser is 175 mm and the tread is 280 mm. Thus, the following kinematic constrains are defined:

$$a \cdot \cos\alpha + r_2 < 280 \text{ mm} - \delta_H, \tag{11}$$

$$c \cdot \cos\alpha + r_4 < 280 \text{ mm} - \delta_H, \tag{12}$$

$$a \cdot \cos\alpha > r_1 + r_2, \tag{13}$$

$$b \cdot \cos\alpha > r_2 + r_3, \tag{14}$$

$$c \cdot \cos\alpha > r_3 + r_4. \tag{15}$$

Note that δ_H (see Figures 5 and 6) is a security parameter, which is used to safety problems due to sensor errors and uncertainties in mechanical parameters.

III. CONTROL ARCHITECTURE

In this section, the strategy to control the actuators is explained. The objective is to explain how the coordinates of the wheels change in order to climb up or climb down a stair. Figure 5 and 6 explain the strategies followed when climbing up and down a stair, respectively.

Three different levels are considered in these schemes. The first level considers the wheel states, which must be achieved in order to avoid any collision between the wheel and the step and to guarantee that the wheel is place stable on the ground. In Figure 5, three branches are defined in order to indicate the increment in horizontal and vertical coordinates, which are denotes as Δ_{hor} and Δ_{ver} respectively. The command associated to Δ_{hor} and Δ_{ver} are *Advance* and *Rise*, respectively. Note that the movement between the states 3 and 4 depends on the wheel pair geometry, which is the second level of the control architecture. A third level of the architecture is defined in order to decide how the command *Rise* is implemented. Thus, *Rise* can be achieved with all the linear actuators (L_1, L_2, L_3 and L_4 with Equations (8-10)), with only one (i.e., the linear actuator of the wheel which is risen) and/or change the angle α with the actuator L_9 (Equation (7)). The two branches defined in Figure 6 to climb down are analogous to Figure 5.

The command *Measure* obtain the distance between each wheel and the nearest obstacle (i.e., the obstacle with the same height that the wheel). *Measure* gets the index of the wheel which is closest to its nearest step (denoted *i*), providing the horizontal d_H and the vertical distance d_V (see Figure 7).

Figure 8 shows the software structure of the control architecture. The first level is $Wheelsx4$, which corresponds with wheel level. Each wheel is controlled considering the equations described in Section II. The second level is *Pair*, where the front and back pair are separated. The first pair controls the actuators of wheels 4 and 3 (L_4 and L_3) and the second pair the wheels 2 and 1 (L_2 and L_1). The third level is *Base* (i.e., wheelchair level), which coordinates the horizontal movement with the vertical movement. This level considered the kinematics equations and restrictions described in Section II and the control strategy. In addition, the procedure to change the vertical position of any wheel is also decided in this level. Finally, the software can generate and plot the trajectory of wheelchair actuators.

In the following subsections, the three levels are explained

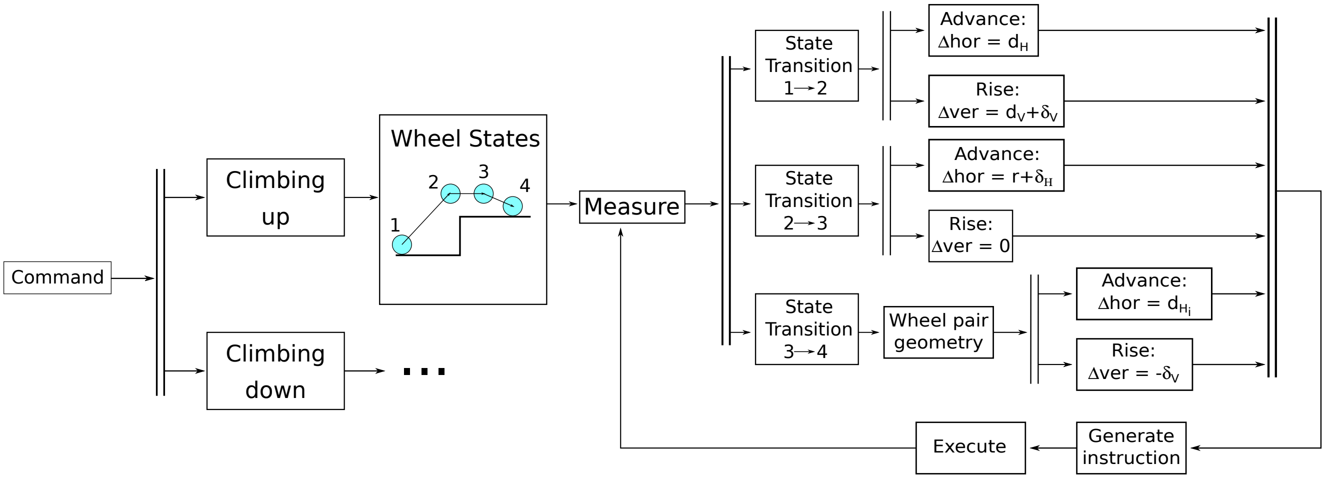

Fig. 5. Strategy followed in order to climb up.

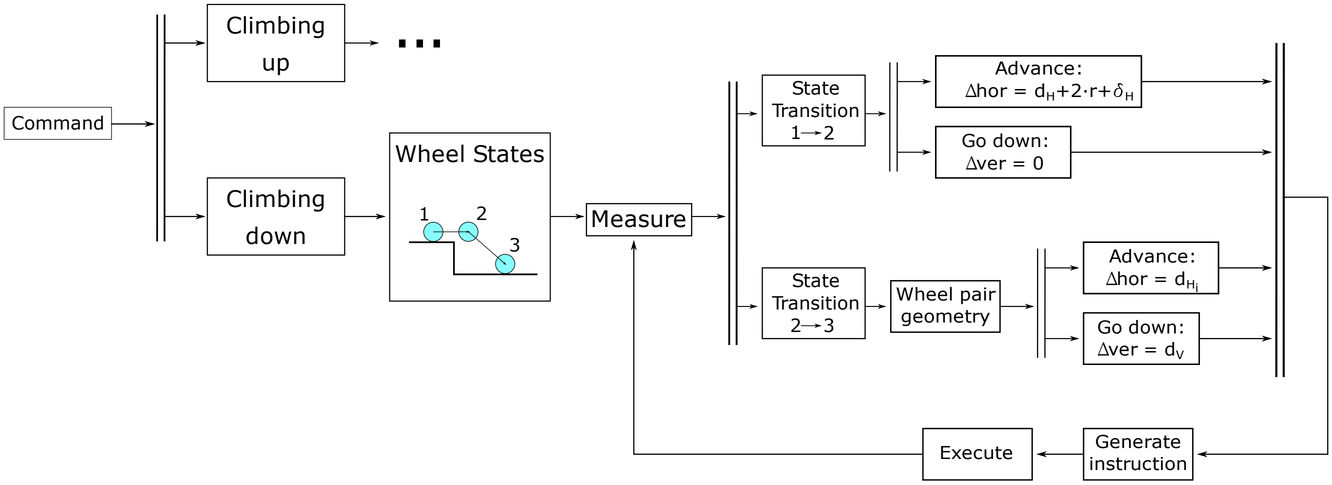

Fig. 6. Strategy followed in order to climb down.

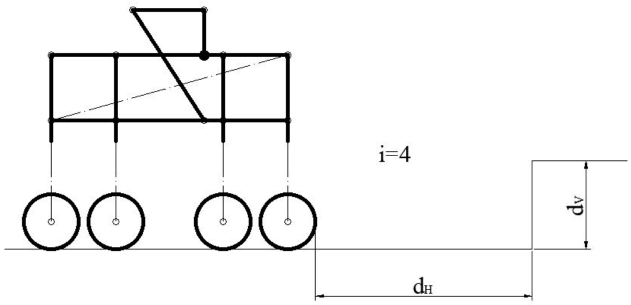

Fig. 7. Practical example of command *Measure*, where closest wheel is $i = 4$.

in detailed.

A. Individual Wheel level

The climb up (see Figure 13) and climb down (see Figure 14) trajectories of an individual wheel is described herein. Both trajectories are divided in the states defined above, which are explain in detail in this subsection. The nomenclature is: i) Δ_{x_i} and Δ_{y_i} are the horizontal and vertical displacement of the wheel i in each instruction, ii) r is the radius of the wheel and ii) δ_H and δ_V are additional displacements, which depends on the sensor precision. Note that δ_H and δ_V are necessary in order to avoid collisions and to guarantee that the wheel is on the step.

1) Climb up - Figure 13:

- State 1. The command *Measure* obtains the distance d_H and d_V of the closest wheel (i).
- State 2. $\Delta_x = d_{H_i}$ and $\Delta_{y_i} = d_V + \delta_V$.
- State 3. $\Delta_x = r + \delta_H$ and $\Delta_{y_i} = 0$.
- State 4. $\Delta_{y_i} = -\delta_V$. The horizontal position Δ_x can be increased if it is possible, reducing the trajectory time. The value of Δ_x depends on the wheel pair and wheelchair level.

2) Climb down - Figure 14:

- State 1. The command *Measure* obtains the distance d_H and d_V of the closest wheel (i).
- State 2. $\Delta_x = d_{H_i} + \delta_H + 2r$ and $\Delta_{y_i} = 0$.
- State 3. $\Delta_{y_i} = -d_V$. Δ_x can be increased if it is possible,

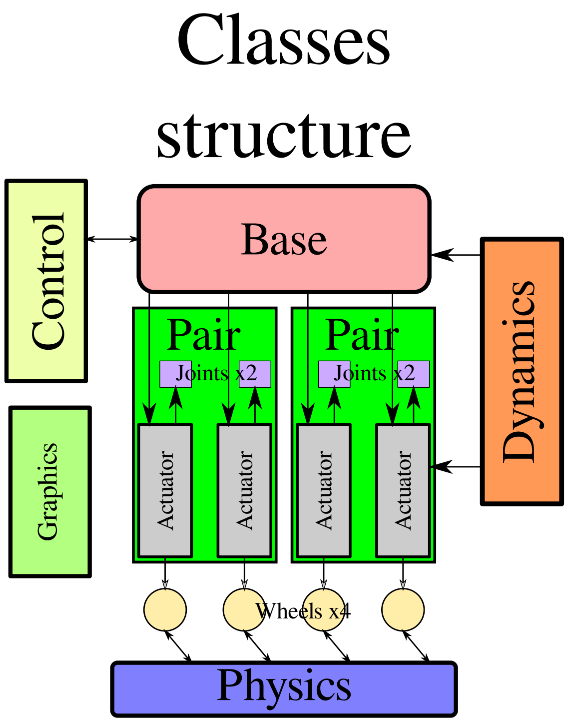

Fig. 8. Software structure of the control architecture.

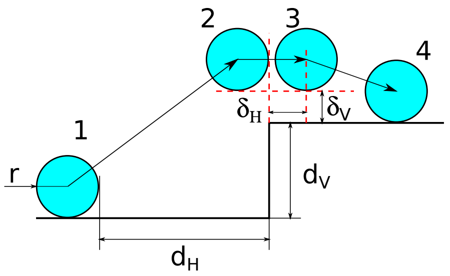

Fig. 9. Individual Wheel level - Climb up.

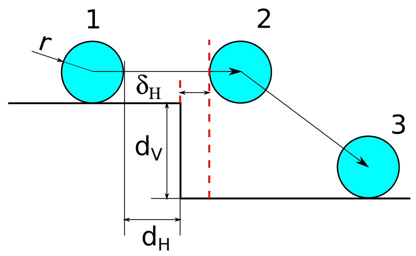

Fig. 10. Individual Wheel level - Climb down.

reducing the trajectory time. The value of Δ_x depends on the wheel pair and wheelchair level.

Note that the rest of the wheels move accordingly, but no collision is guaranteed because they are further than the wheel i.

B. Wheel pair level

The wheelchair of Figure 2 can be considered as two independent wheel pairs. Thus, the first wheel (4 or 2) climbs up (or climbs down) firstly the step. Let us denote this wheel as i. Thus, the second wheel of the pair is $i-1$.

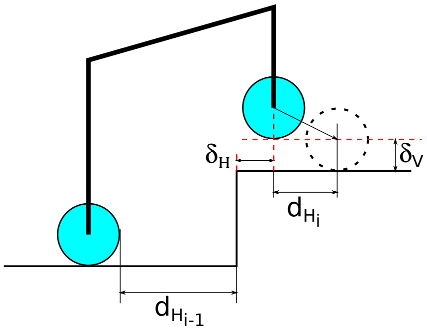

Fig. 11. Wheel pair level - Climb up.

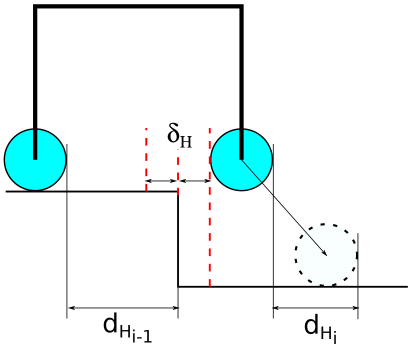

Fig. 12. Wheel pair level - Climb down.

1) Climb up - Figure 11: In this level, it must be considered the State Transition wheel from 3 to 4. Let us defined the front wheel as wheel i and the back wheel as $i-1$. Thus, the pair geometry level in the state transition from 3 to 4 is as follows:

- Wheel i. *Measure* obtains $d_{H_{i-1}}$ of the wheel $i-1$. Thus $\Delta_{x_i} < d_{H_{i-1}}$ when wheel i achieves the individual wheel state 4.
- Wheel $i-1$. *Measure* obtains d_{H_i} of the wheel i. Thus $\Delta_{x_{i-1}} < d_{H_i}$ when wheel $i-1$ achieves the individual wheel state 4.

2) Climb down - Figure 12: In this level, it must be considered the wheel which is climbing down. Thus, if the front wheel (denoted as wheel i) is climbing down (from States 2 to 3), this wheel must be placed on the ground before the back wheel (denoted as $i-1$) get out of the step, in order to guarantee that the stability of the mechanism. Analogously, if the wheel $i-1$ is climbing down (from States 2 to 3), the wheel i also have to be placed on the ground. Thus, wheel pair geometry considers what wheel is climbing down. In addition there is not wheel pair geometry in state transition 1 to 2. Therefore, the pair geometry level in the state transition 2 to 3 is as follows:

- Wheel i. *Measure* obtains $d_{H_{i-1}}$ of the wheel $i-1$ and $\Delta_{x_i} < d_{H_{i-1}} + r - \delta_H$ when wheel i achieves the individual wheel state 3, guarantying that the wheel $i-1$ is placed on the ground.

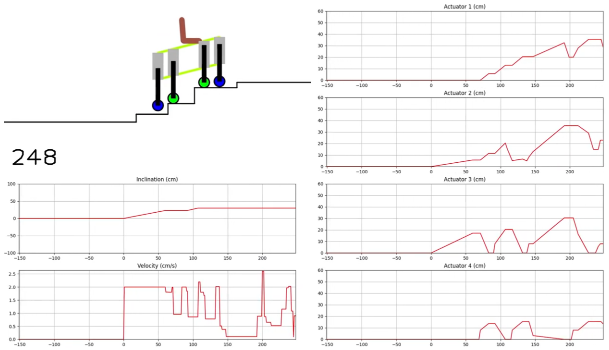

Fig. 13. Application example of the wheelchair climbing up a stair with different steps.

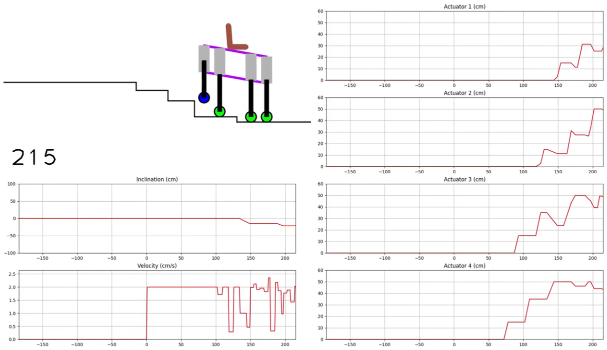

Fig. 14. Application example of the wheelchair climbing down a stair with different steps.

- Wheel $i-1$. *Measure* obtains d_{H_i} of the wheel i and $\Delta_{x_{i-1}} < d_{H_i} + r - \delta_H$ when wheel $i-1$ achieves the individual wheel state 3, guarantying the wheel i is placed on the ground.

C. *Wheelchair level*

This level coordinates the two wheel pairs, deciding the horizontal velocity of the chair in order to guarantee that one wheel of each wheel pair is on the ground and there is not collision between wheels and obstacles. In addition, this level coordinate the length of the actuators $L_1 - L_4$ in the *Rise* command. This coordination depends on the wheel is changing its height. Thus, the movement are as follows:

- Wheels 4 and 1: The height is achieved by changing α. Then, if there is not enough room of the actuator to achieve the height required, the height of the wheelchair is changed until the actuator can achieve it.
- Wheels 2 and 3: As opposed to wheels 4 and 1, change the height of the wheelchair. Then, if the height is not achieved, α is changed.

IV. APPLICATION EXAMPLE

In the following video link [1] it can be seen several trajectory examples of the wheelchair. Figures 13 and 14 show a snapshot of this videos. In this figures, the horizontal velocity of the wheelchair, the inclination (related to angle α) and $L_1 - L_4$ are plotted. This application example considers that the actuators can follow the desired velocity reference without considering the maximum acceleration. This will be considered in future works, where the dynamic control will be designed and implemented.

V. CONCLUSIONS

This work defines the first kinematic control architecture for the novel design proposed in [3]. According to [1], the trajectories generated for the actuators can be used to implement in practice this control. In addition, this control architecture will be used, in future works, in order to optimize the mechanical parameters $(a, b, c, d, L_i, r_i, \ldots)$ in order to reduce the total climbing up or down time. Finally, in the following link [2] you can see all the code of the project.

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[1] `https://www.youtube.com/playlist?list=PL-cQTqyWA2d1upFVvzsNcJ0bn3QE4KyfV`

[2] `https://github.com/pedrogil1919/Structure`