A Novel Approach for a Leg-based Stair-climbing Wheelchair based on Electrical Linear Actuators

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Abstract: The objective of this work is to develop a novel low-cost wheelchair capable to climb stairs (according to Spanish building regulation) and any obstacle similar to a step, to drive over uneven terrain such as cobblestones and adjust the height of the seat. The contribution presented in this work can be included into the leg-based stair-climbing mechanism classification. This work is a novel solution based on a previous patent, which proposed a wheelchair composed of nine linear actuators controlled by a pneumatic system. This novel approach proposes a mechanical modification in order to increase the flexibility of the mechanism, allowing the wheelchair to move up and down without changing the orientation, also guaranteeing the horizontal position of the user. In addition, the electric linear actuator presents some advantages with respect to the pneumatic system proposed in the previous design, being this wheelchair easier to be controlled. This works also presents the first prototype developed.

1 INTRODUCTION

According to a study developed by the Observatory of Physical Disability (Fernández, 2016), 81% of people with physical functional diversity say they find barriers to leave their home, mainly due to the architectural obstacles that they encounter. Although various laws have been developed in Spain, that aim to make public and private spaces accessible, the limitation of these barriers supposes a very considerable reduction in the welfare of life of people with disabilities. Specially, people with movement disabilities, which require the use of a wheelchair, are affected by the presence of curbs, stairs, irregular obstacles and the inability to easily access places that are accessible to other users, as is the case of non-adapted tables or countertops.

This work is focused in the mobility associated to stairs and any obstacle similar to a step, which can be found indoor and outdoor. The authors of this work collaborate with a non-profitable organization (http://padrinotecnologico.org/), whose main concern is related with the development of devices for people with physical disabilities, especially for children. One of the most demanded devices is a low-cost stair-climbing wheelchair, which can climb Spanish stairs (Fomento, 2010) and can overpass any obstacle similar to a step. In addition, this device must allow the adjustment of the wheelchair height, helping the user in different scenarios, such as the access to tables or countertops of different heights, or the possibility to hold conversations with other people who are standing up. Finally, other requirement included the wheelchair to be able to drive over uneven terrain such as cobblestones. The authors would like to use this prototype to apply for future CYBATHLON races (http://www.cybathlon.ethz.ch/).

It is well known that there are several stair-climbing assistive mechanisms for the disabled people, see for example the thesis written by (Lawn, 2002). Research on chair-type mechanisms capable of climbing stairs is a very active research topic nowadays. In (Tao, 2017), the technical advantages and disadvantages of different types of electric powered wheelchairs with stair-climbing system are outlined and an overall comparison of the control method, cost of mechanical manufacture, energy consumption and adaption to different stairs is introduced. Table I in (Tao, 2017) presents an excellent classification of these mechanism, where the reader can compare the types of wheelchairs that incorporate a stair climbing system and whether they have been commercialized or not. According to this

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reference, wheelchairs can be classified into: 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.

Track-based stair-climbing mechanisms have been successfully commercialized. These mechanisms are based on the interlocking effect between the track's outer teeth and the steps' sharp corner. For example, TopChair-S (Heinrich, 2016) is a good example of that. Other example based on big wheels, which can climb stairs is the PW-4x4Q Stair Climbing Wheelchair (Wheelchair88, 2017). These two commercial solutions present two main problems. The first one is that they are economically unaffordable for families with average incomes. The cost of these commercial solutions are around 12500 € for PW-4x4Q and 15500 € for TopChair-S. The second one is that they utilize the two most used options: large wheels whose relative height can be modified (PW-4x4Q Stair Climbing Wheelchair) and caterpillar mechanism (TopChair-S). Performance of these two solutions depend on the grip of the material to the obstacle, which can be deteriorated, making the cost of the solution even more expensive due to the maintenance required.

The wheel cluster–based stair-climbing mechanism is relatively compact and can easily switch to wheeled mobile mode when running on level ground. Examples of these mechanism are (Quaglia, 2011) and (Quaglia, 2017), where a cluster of three wheels is proposed. In (Quaglia, 2011), a mechanism with only one motor and a transmission system per locomotion unit is proposed. The wheelchair passively changes its locomotion, from rolling on wheels ("advancing mode") to walking on legs ("automatic climbing mode"), according to local friction and dynamic conditions. In (Quaglia, 2017), a track-based stair-climbing is combined with the cluster of three wheels in order to improve the wheelchair stability.

A good example of hybrid stair-climbing mechanism is the one proposed by (Morales, 2004). In this work, a chair model capable of climbing stairs was presented. This mechanism has been improved in terms of kinematic control, see for example (Morales, 2013) and (Chocoteco, 2016). This mechanism can be adapted to different steps and obstacles, generating smooth and comfortable trajectories for the user. However, the mechanism is complex, which has not made possible its commercial use to date.

Leg-based stair-climbing mechanisms can be classified into biped and parallel mechanism. For example, the reference (Sugahara, 2006) developed a biped stair-climbing mechanism based on a Stewart platform. This mechanism can walk up and down a stair riser height of 150 mm continuously carrying 60 kg. A stair-climbing vehicle named "Zero Carrier" with eight legs was proposed by (Yuan, 2004). In (Wang, 2014) a concept of an eight-legged wheelchair aiming at improving the limitations of the Zero Carrier design was proposed. The eight legs are grouped into two independent frames of four legs each. The two frames can change the relative horizontal position between them. Thus, height legs can be substantially reduced with respect to the design proposed in (Yuan, 2004). However, the mechanism needed to move horizontally the frame may be an inconvenient when heavy loads must be carried. According to (Tao, 2017), although these leg-based stair-climbing vehicles are complex, have high costs, and have unconventional appearances, they are able to achieve the core function of stair ascent and descent and provide some innovations in climbing wheelchair design.

The contribution presented in this work can be included into the leg-based stair-climbing mechanism group. This work is a novel solution based on the patent (Kluth, 1986), which has not been built yet, nor commercialized or referenced for other authors (up to the authors knowledge). This original patent proposes nine linear actuators controlled by a pneumatic system. Eight of these actuators are used to climb the stairs, similar to the contribution proposed in the references (Yuan, 2004) and (Wang, 2014). In addition, a ninth actuator is proposed to guarantee a horizontal position of the user with a minimal of actuators length, which is one of the problems of the solution proposed in (Yuan, 2004). Besides this, it is not necessary a relative displacement between each four legs frame, which is the main problem of (Wang, 2014). The work presented also proposes a mechanical modification of (Kluth, 1986), which changes the configuration of the ninth actuator. This modification increases the flexibility of the mechanism, allowing the wheelchair to move up and down without changing the orientation of the chair and guaranteeing the horizontal position of the user, as in references (Yuan, 2004) and (Wang, 2014). Moreover, the electrical linear actuator presents some advantages respect to the pneumatic system proposed in (Kluth, 1986), being this wheelchair easier to be controlled. Finally, this work shows the first prototype developed and built in their laboratory.

This paper is organized as follows. Section 2 describes the mechanical design, paying attention to placement of the linear actuators in order to guarantee the climbing of standards stairs defined in (Fomento, 2010). Section 3 presents the first low-cost prototype developed in our research group. In this section, the main components are also described. Finally, Section 4 discusses the conclusions and future works.

2 MECHANICAL DESIGN

The wheelchair mechanical design considers the less favourable stairway according to (Fomento, 2010), which is shown in Figure 1. In addition, the proposed leg-based stair-climbing mechanism can drive over uneven terrain such as cobblestones and adjust the height of the chair, which can help to the user in different scenarios, such as tables with different heights or hold conversations with other people who are standing up.

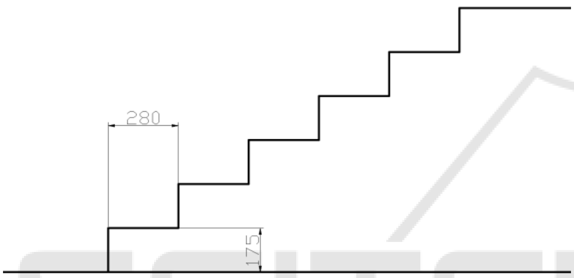

Figure 1: Most unfavourable stairway according to (Fomento, 2010).

This section proposes: i) the wheelchair mechanism, where all the variables to be configured are defined, ii) the kinematic equations (direct and inverse kinematic model), which are used in the control of the wheelchair, and iii) the definition of the wheelchair constant parameters according to the stair defined in Figure 1.

2.1 Wheelchair Mechanism Description

Figure 2 shows a 3D description of the proposed prototype made with the 3D CAD software for product development INVENTOR (of AUTODESK). This wheelchair has 17 electrical motors. Eight of them are connected to one of the eight each wheels intended to move the wheelchair. The rest of the electrical motors are connected to linear actuators. These linear actuators are used to change the height of the corresponding wheel (eight of them). The last one is used in combination with the articulated mechanism connected to the T (green part in figure) in order to keep the horizontal position of the chair placed on top of it. Note that this T is fixed by two articulated joints to the frame.

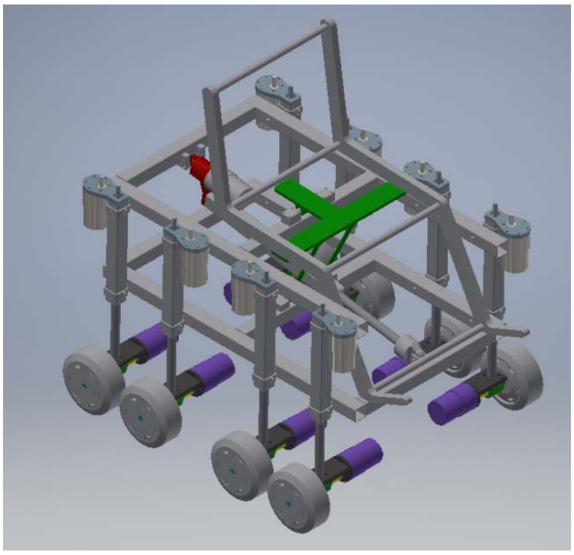

Figure 2: 3D description of the proposed prototype.

In order to better explain the mechanism, Figure 3(a) shows the left side of the wheelchair, where the 4 linear actuators connected to the left four wheels and the linear actuator placed in its diagonal are shown. It should be noted that the mechanical model proposed in (Kluth, 1986), which is shown in Figure 3(b), has the actuator L_9 placed between the joints of actuators L_2 and L_3. The model (Kluth, 1986) cannot guarantee the horizontal position if a step (or any obstacle) is climbed up and down without a change in the orientation of the mechanism. In this figure, it can be seen:

- The main constant dimensions (a, b, c, d and r). These variables must be defined according to the dimensions of the obstacles, as the stair step defined in Figure 1.
- Variables needed to change the leg heights and to ensure the horizontal position of the users (L_1, L_2, L_3, L_4 and L_9). The length of the linear actuators L_1, L_2, L_3 and L_4 depend on the relative position of each wheel with respect to the obstacle. The length of the linear actuator L_9 depends on the angle of the frame respect to the horizontal reference. The kinematic model, which is described below, is needed in order to control this mechanism.
- The wheelchair is propelled by eight electrical motors connected to the eight wheels. The position control of these motors depends on the relative horizontal position

between each wheel (the full structure) and the obstacle.

In this work the variables defined into Figure 3 are set according to the stair profile defined into Figure 1.

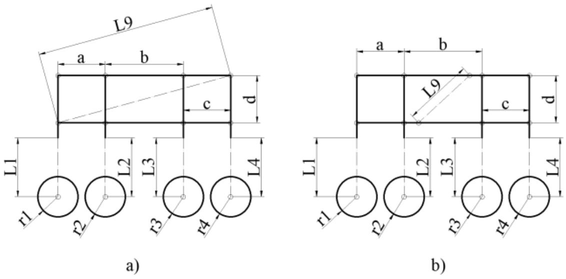

Figure 3: Main structure with variables. Variables in capital letters are calculated with the kinematic model defined bellow. Variables in small letters must be configured according to obstacles. (a) Wheelchair proposed in this work. (b) Wheelchair proposes in (Kluth, 1986).

First of all, Figures 4 and 5 show illustrative examples of how the mechanism works. Figure 4(a) shows how the linear actuator L_9 can be configured in order to keep constant the rest of linear actuators for a constant slope. Figure 4(b) shows how to keep each linear actuator perpendicular to its corresponding step.

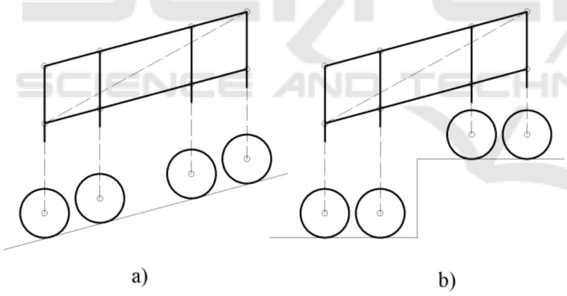

Figure 4: Main structure configuration for (a) slope and (b) stair.

Figure 5 shows how the seat can be set horizontal without any additional actuator (see green T structure in Figure 1). Note that, the linear actuators L_1 to L_8 must be vertical (i.e., perpendicular to a horizontal reference) in order to guarantee the horizontal position of the chair and to reduce the strains caused by the weight of the structure and the user.

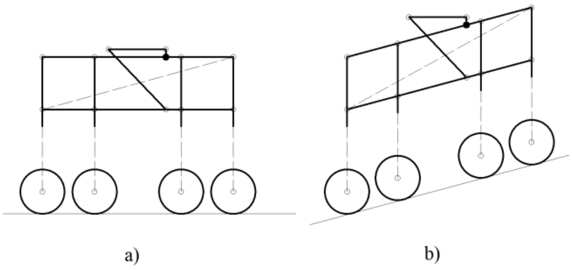

Figure 5: Permanent horizontal platform fixed to the main structure when (a) the wheelchair is horizontal and the (b) the wheelchair is climbed a slope.

2.2 Direct Kinematic Model

The direct kinematic model can be deduced from Figures 6 and 7. The objective is to relate the Cartesian coordinate of each wheels 2, 3 and 4 respect to the first wheel (see the values of (x_1,y_1), (x_2,y_2), (x_3,y_3) and (x_4,y_4) in Figure 6). The reference coordinate system is defined at the centre of the first wheel (x_1,y_1).

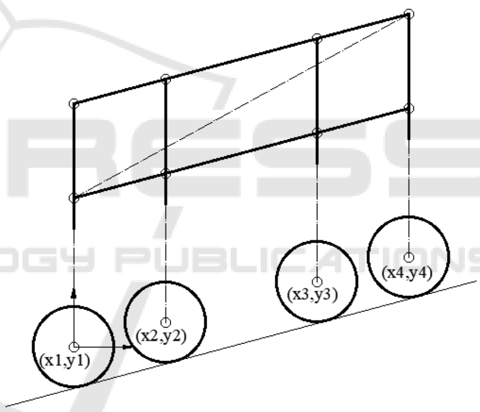

Figure 6: Cartesian coordinates of each wheel.

As it was mentioned above, the linear actuators L_1-L_4 (L_5-L_8 on the other side) must be kept vertical in order to guarantee the horizontal position of the chair. Thus, the rectangle of the structure (see for example Figure 5(b)) must be changed into a rhomboid with an angle equal to β in order to guarantee this restriction (see Figure 7). In addition, the angle α, which depends on β, is needed to obtain the relationship between horizontal and vertical relative position between the origin (x1,y1) and the centres of the other wheels: points (x_2,y_2), (x_3,y_3) and (x_4,y_4).

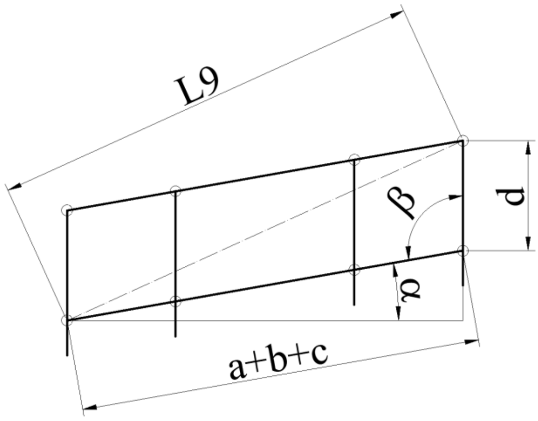

Figure 7: Relationship between the structure dimensions and the angles α and β.

According to Figure 7, the angles α and β are related as follows:

$$\alpha = \beta - 90, \quad (1)$$

where β is calculated as follows:

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

where L_H is equal to a+b+c. If the variables in Figure 3 are considered, the coordinates of the centre of each wheel is defined into Equations (3), (4) and (5) as follows:

$$\begin{gathered} x_2 = a \cdot sin(\alpha) \\ y_2 = a \cdot cos(\alpha) + L_1 - L_2 \end{gathered} \quad (3)$$

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

$$\begin{gathered} x_4 = (L_H) \cdot sin(\alpha) \\ y_4 = (L_H) \cdot cos(\alpha) + L_1 - L_4 \end{gathered} \quad (5)$$

Note that, as it was mentioned above, if Equations (2) and (3) are achieved, the actuators L_1, L_2, L_3 and L_4 can keep a horizontal position of the chair (see Figure 4). Note also that Equations (3), (4) and (5) are valid also for actuators 6 (L_6), 7 (L_7) and 8 (L_8), respectively, being the origin the wheel 5. Thus, if the objective is to climb a stair, the following restriction must be achieved:

$$L_1 = L_5;\ L_2 = L_6;\ L_3 = L_7;\ L_4 = L_8; \quad (6)$$

2.3 Definition of the Constants Parameters (a, b, c, d and r)

An illustrative example for the stair defined in Figure 1 is presented herein. The slope of the stair defined in Figure 1 is equal to 30º. Then, the maximum value for α must be 30º. Note that the pairs formed by wheels 1 – 2 and 3 – 4 must be placed on the same step. Thus, the following restrictions must be achieved:

$$\begin{gathered} a \cdot cos(\alpha) + r_2 < 280\ mm \\ c \cdot cos(\alpha) + r_4 < 280\ mm\text{'} \end{gathered} \quad (7)$$

if the stair is climbed according to Figure 4(b). In addition, if the prototype shown in Figure 3(a) is considered, the following restrictions must also be achieved:

$$\begin{gathered} a \cdot cos(\alpha) > r_1 + r_2 \\ b \cdot cos(\alpha) > r_2 + r_3. \\ c \cdot cos(\alpha) > r_3 + r_4 \end{gathered} \quad (8)$$

This condition guarantees that the wheels have a gap between them when the maximum value of α is reached. For example, let us consider the wheelchair configuration of Figure 8 and the geometry of the stair defined in Figure 1. Note that configuration shown Figure (8a) is useful to climb the first step with wheels 4 and 8. However, for value of α = 15º, the wheels 3 and 4 (7 and 8) cannot be placed in the same step because the restriction defined in Equation (7) cannot be achieved. Therefore, the value of α must be increased. The maximum value of α, according restriction defined into Equation (8), is 30º (see Figure 8(b)), which is the slope of the stair defined into Figure 1. With this value for α, the rest of steps can be climbed.

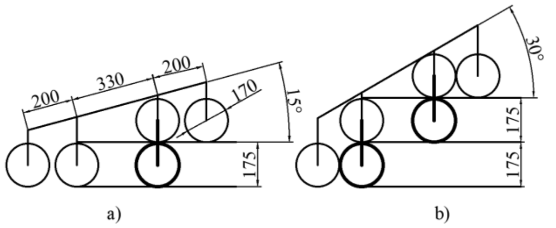

Figure 8: Wheelchair configurations to climb the steps of the stair defined in the Figure 1. (a) Configuration to climb the first step. (b) Configuration to climb the rest of the steps.

2.4 Inverse Kinematic Model

The inverse kinematic model proposed in this work consists in defining firstly an angle α suitable for climbing the stairs. Note that the control of 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 (2) as β = α + 90. Therefore, the length of the diagonal (L_9) is obtained as follows:

$$L_9 = \sqrt{d^2 + L_H^2 - 2 \cdot L_H \cdot d \cdot \cos(\beta)}. \tag{9}$$

Note that, if Figure 7 is considered, the value for α can be obtained α=15º (β=105º) in Figure 8(a) and α=30º (β=120º) in Figure 8(b). The value of L_9 can be calculated from Equation (9).

If L_1 (L_5) is assumed equal to zero, which minimizes the actuator lengths, the variables L_2 (L_6), L_3 (L_7) and L_4 (L_8) can be obtained from Equations (3), (4) and (5), respectively. These equations are:

$$L_2 = a \cdot cos(\alpha) + L_1 - y_2 \tag{10}$$

$$L_3 = (a + b) \cdot cos(\alpha) + L_1 - y_3 \tag{11}$$

$$L_4 = (L_H) \cdot cos(\alpha) + L_1 - y_4 \tag{12}$$

If restrictions defined into Equations (9)-(12) are achieved, the legs are kept perpendicular, guarantying the configurations shown in Figure 4(b).

2.5 Electronic Control

The wheelchair prototype would be prepared to control any actuator using an electronic control based on Arduino (Arduino, 2019) boards for low level control tasks and a Raspberry Pi to perform the vision tasks needed to approach the obstacles and the synchronization between different control boards.

There are three main control tasks. The first one is needed to keep the seat horizontal and it is based on a gyroscope and an Arduino micro board. The gyroscope used will be the well-known ADXL345 that, while being low cost, is reliable and has a low power consumption. Gyroscope, Arduino and actuator form a classical feedback control system to ensure that the angle α returns to 0 after a change as shown in section 2.5. This control system is not connected to the Raspberry since its work is completely independent.

The second control task is the one related to the eight electric motors connected to each wheel. In our work, two possibilities are considered. The four wheels on each side can be controlled in parallel being, that way, only one motor for all practical purposes. Then, the control is really simplified but there is a loss of flexibility. If more flexibility is needed, an independent motor control could be considered. The control will be performed using several Arduino micro boards connected to dual full-bridge drivers L298. These Arduino boards are in charge of the low level motion instructions while the Raspberry Pi does the high level control after calculations based on image processing, sensors information (if needed) and a joystick control operated by the user. These structure could be simplified in a future prototype if four motors drivers and an Arduino Mega are used.

Finally, the third control task is the needed to climb the stairs as shown below in section 3. In this case there are also eight motors but it is clear that each pair in each side must be controlled at the same time. The control in this case is also based in Arduino boards and dual full-bridge drivers but there is no user input and it is mainly automatic. That automatic task will be triggered by the Raspberry Pi after the vision system gets to the optimum position.

3 EXAMPLE OF TRAJECTORY

In this section, an example of a trajectory to climb the stair defined in Figure 1 is explained. Figure 9 shows the initial configuration of the wheelchair, where the actuator lengths are defined as follows (the restriction defined in Equation (6) is applied to all equations for L_1, L_2, L_3 and L_4):

$$\begin{gathered} L_1 = 0 \\ L_2 = a \cdot sin(\alpha) \\ L_3 = (a + b) \cdot sin(\alpha) = y_{s1} - y_{s0} \\ L_4 = c \cdot sin(\alpha). \end{gathered} \tag{13}$$

Note that the value of α is obtained for the third restriction (and in Figure 1 is α=15º). When $x_4 > x_{s0}$, the wheel 3 rise up to $y_3 = y_{s1}$. Note that the value of α must be increased in order to that wheels 3 and 4 can be placed into the first step. This value for α must be achieved before $x_3 + r_3 \geq x_{s0}$. Figure 10 shows an example of this case, where the final actuator lengths are calculated as follows:

$$\begin{gathered} L_1 = 0 \\ L_2 = a \cdot sin(\alpha) \\ L_3 = (a + b) \cdot sin(\alpha) > y_{s1} - y_{s0} \\ L_4 = L_H \cdot sin(\alpha) - y_{s0}. \end{gathered} \tag{14}$$

Then, the height of wheel 2 must be equal to y_{s1} ($y_2 = y_{s1}$) before $x_2 + r_2 \geq x_{s0}$. Figure 11 shows an example to achieve that. The actuator lengths are as follows:

$$L_1 = y_{s2} - y_{s0} - (a + b) \cdot sin(\alpha)$$
$$L_2 = y_{s2} - y_{s0} - b \cdot sin(\alpha) = y_{s1} - y_{s0}$$
$$L_3 = y_{s2} - y_{s1} \qquad (15)$$
$$L_4 = c \cdot sin(\alpha)$$

When $x_2+r_2 \geq x_{s0}$, the wheel 2 rises up to $L_2=0$. When $x_3+r_3 \geq x_{s1}$, the wheel 3 rises up to $L_3=0$. Figure 11 shows this configuration. The actuator length are as follows:

$$L_1 = y_{s1} - a \cdot sin(\alpha)$$
$$L_2 = L_3 = 0 \qquad (16)$$
$$L_4 = c \cdot sin(\alpha)$$

The next restrictions are analogous to (15) and (16) but updating the height of the steps. Figure 13 shows an example of how to climb the third step (Figure 11 and 13 shows the same wheelchair configuration). The optimization of the structure for a group of stairs must be done in order to reduce the cost of the structure and increase the speed. This is out of this work and will be developed in future works.

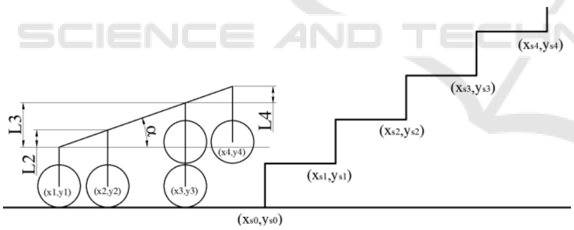

Figure 9: Initial configuration of the wheelchair when it starts to climb the stair.

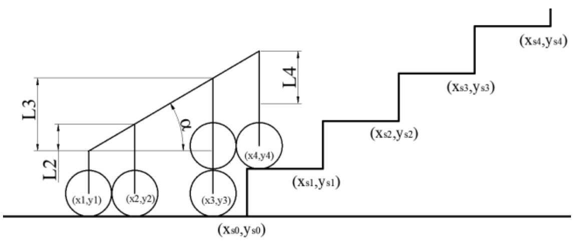

Figure 10: Example of configuration in order to climb the first step.

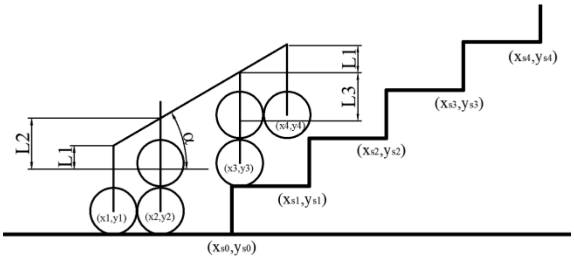

Figure 11: Example of configuration in order to climb the second step.

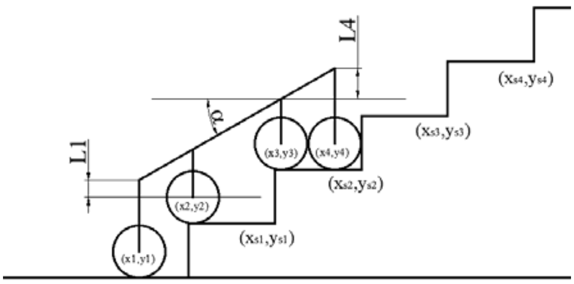

Figure 12: Example of configuration previous to climb the third step.

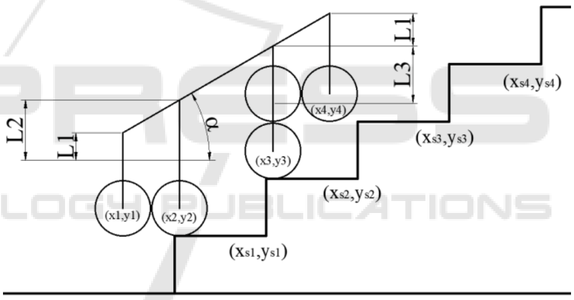

Figure 13: Example of configuration in order to climb the third step.

Finally, it should be noted that the final wheelchair prototype will be based on an external vision sensor, which will give the relative position information between the structure and the stair (or any obstacle). This is out of the topic of this work.

4 PROTOTYPE OF THE WHEELCHAIR

The first prototype is designed according to the geometrical data of Figure 8. This prototype has been designed, developed and built in our lab, using low-cost materials. In Figure 14, a different view of the mechanism of Figure 2 is shown. Note that the linear actuators and the mechanism guarantee the horizontal position of the user according to the kinematic model explained above.

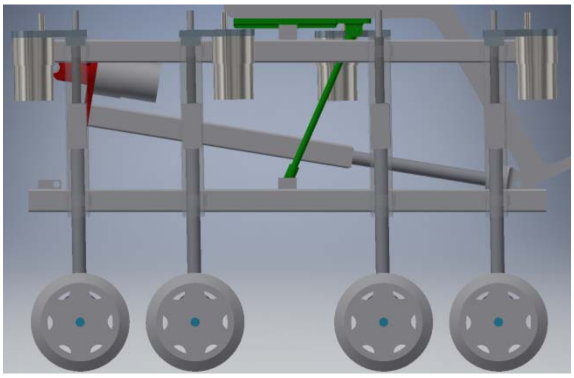

Figure 14: Main structure prototype.

It should be highlighted that each linear actuator is based on a threaded bar fixed to a squared base straight prism. When the threaded bar rotates, the vertical position of the prism, which is connected to the bar, changes. This threaded bar is fixed to the support of each wheel. Details of the linear actuator are shown in Figure 15. Each linear actuator is driven by an electrical motor through a pulley belt transmission system (see in Figure 16 of the built prototype).

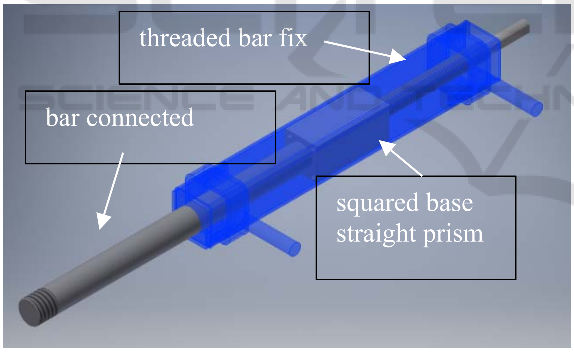

Figure 15: Linear actuator. Designed, developed and built in our laboratory.

Figure 17 shows a picture of the preliminary built prototype (1:2 scale). Note that, the chair has not been placed yet. In addition, electrical motors and pulley belt transmission system are not fully placed.

Figure 18 shows the details of the ninth linear actuator and the mechanism that guarantees the horizontal position of the users.

Figure 16: Details of the transmission between the electrical motor and the linear actuator. 30 MXL 025 and 22 MXL 025 timing pulley and 44 MXL timing belt.

Figure 17: First built prototype (1:2 scale). Main structure. All components, except the electrical motor and the pulley belt transmission system, have been designed, developed and built in our laboratory.

Figure 18: First built prototype (1:2 scale). Details of the ninth linear actuator and mechanism that guarantees the horizontal position of the users.

5 CONCLUSIONS AND FUTURE WORKS

A novel approach for a leg-based stair-climbing mechanism is proposed, in this work. This approach consists of a mechanical modification of a previous patent. This mechanical modification increases the flexibility of the mechanism, allowing the wheelchair to move up and down without changing the orientation, which has not yet been implemented in practice. In addition, electrical linear motors are used, instead the pneumatic system proposes in the patent.

The description of the mechanism and the kinematic equations (direct and inverse) have been deduced. A preliminary prototype, which will be finished by the final version of this work, has been introduced.

Future works will consider the control system and the external vision needed to locate the wheelchair with respect to the obstacle. In addition, once this 1:2 scale prototype is validated, a 1:1 low cost prototype will be built and a user test will be performed within the facilities of the research group.

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