DEVELOPMENT OF AN ELECTRIC WHEELCHAIR DESIGNED TO CLIMB STEPS AND TO BE CONTROLLED BY THE BODY MOVEMENT, ACCORDING TO PERUVIAN LAWS

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ABSTRACT

This document presents the design and implementation of an electric wheelchair, which be able to move freely around urban areas in Peru and be able to be controlled by people without upper arms. In the mechanical design, we started by selecting commercial components and continued with geometric and dynamics restrictions. In the electronic area, based on the mechanical design and Newton's laws we calculated the parameters of the actuators and then, by using inertial sensors we calculated the user inclination and converted this data into velocity of the wheelchair. Likewise, we created an user interface to adapt the wheelchair commands to each user. Thus, this device will almost eliminate the dependence of disabled people from another person, and it will improve their feelings of independence.

Keywords: wheel cluster based stair-climber, inertial sensor.

1. INTRODUCTION

In 2011, The World Bank and the World Health Organization did a survey which showed that at least 1.5% of people around the world suffered from a disability [1]. In a similar way, the National Institute of Statistics and Informatics indicates that impairment people in Perú is more than 5.2%, and it is expected that this percentage will continue increasing [2]. Both surveys illustrates that the most common form of disability is the walking impairment or the capability to move the legs, thus these people have to use crutches or wheelchairs to translate themselves in their daily environment. As response to this reality, the government of Peru has created social policies, rules and regulations which look for the decrease of discrimination and foment the integration of impairment people into our society. The general law of the person with disabilities [3] and the norm of accessibility for people with disabilities [4] are proof of this. This rule, gives the guidelines for new buildings to have facilities for disabled people in wheelchairs, so they can displace freely and also indicates that old buildings should adapt to this standard.

Around the world, multiple companies developed wheelchairs which a similar common objective: provide users as much autonomy and independence as possible .. Last decade of the 90s and early 21st century, Dean Kean (creator of the Segway) and the Jhonson & Jhonson Company created I-BOT [5], the main characteristic of this wheelchair is the Self-Balancing System that is able to move on two wheels on paved terrain, move on four wheels on more rigorous terrain and even can climb stairs. Another electric wheelchair developed in Europe is SCALEVO [6], the design of this wheelchair allows the user to move through irregular and sloping terrain, climb stairs and adjust the height or inclination of the chair for greater comfort. In Asia, the Japanese company called RINSHOU developed a convertible wheelchair, which adapts itself to every day life actions such as eating, sleeping or going to the bathroom [7]. The different kind of electric wheelchairs named before facilitate the life of impairment people; nevertheless, these wheelchairs use manual controllers (such as joystick or bottoms) so only people with hand or upper arms are able to control it.

This project proposes a novel design and a partial implementation of a electric wheelchair that allows impairment people move freely in urban areas designed according to Peruvian laws. Besides, this wheelchair could be controlled by people without arms or hands because it makes use inertial sensors to convert the inclination angle of the user body into velocity and direction for the wheelchair. Finally, we developed an user interface that allows sensors to be calibrated in order to be possible control the wheelchair by different people without the necesity of change the configuration of the main controller. In that way, we want to elminate the possible injuries which could be generated when the pacient or another person propulse a manual wheelchair. Besides, disabled people will increase their feeling of freedom because they will not need another person assist them permanently.

2. METHODOLOGY

In order to design correctly the proposed wheelchair, it has been considered the main characteristics of the final user, peruvian laws for construction of new buildings and regulations for urban design. The Triple-Delta and Triple-Star wheel mechanism were designed based on these requirements and restrictions. Then, these mechanisms were fixed to the main structure, which purpose is to support the user and also the electrical components. Finally, the main features of the motor were

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calculated, so allowing the wheelchair to move on an inclined surface and climb steps. We used inertial sensor to calculate the inclination of the user's body, and then we scaled this inclination to determine the velocity of the wheelchair.

We divided the project in two parts, the first part is the design and the second one is the implementation. Each part include the mechanical and electronic development of the wheelchair.

2.1 Wheelchair Design

On the mechanical area, the requirements and restrictions for the prototype were defined according to the laws in force in Peru. Then, a geometric analysis was performed to select the dimensions of tires and transmission elements for the triple-wheel. The design was simulated in Solidworks, where the construction material was assigned to the structure in order to get its physical properties.

On the electronic design, the inertial sensors (MPU6050) was conditioned in order to read their data through the I2C protocol. Then, we created an interface to test the state of the sensors and finally, we programmed the control algorithm and manufactured the power circuits.

2.2 Wheelchair implementation

The construction of the wheelchair prototype started with the assembly of the main body by using commercial steel A-36. Then, the two triple wheel mechanism was properly assembled by placing the wheels, bearings and chains properly. Finally, the chassis was attached to the wheels of the chair forming a single solid ready to move around the environment.

The electronic circuits were attached to the main body and the cables were fixed to the same structure. Two different set of batteries were used, the first one was for the entire power circuit and the second one was for the control circuit (we eliminated the mass of the second set of batteries for our calculus). Finally, we used the MyRio controller due to its ability to transmit information through Wi-Fi, in that way we avoid the presence of many wires during test.

3. MECHANICAL AND ELECTRICAL DESIGN

3.1 Requirements and restrictions

First of all, we considered as final user children of 11 years old; therefore, the physical features were taken of a study made in Perú [7] and the average walking velocity was taken of [8].

Secondly, the wheelchair must facilitate that disable children can do their activities in their local neighbor without any problem, so they have to be able to move in parks, common areas, streets and private or public institutions. Therefore, we used the Peruvian rules A.120 [4], A.010 [9] and GH.020 [10] from the National Building Regulation, because these rules point out the requirements to facilitate the access and transit of people in urban areas.

Finally, Table I shows a summary of the main restrictions based on user characteristics and Peruvian regulation. In addition, Table II shows the requirements that the wheelchair proposed must have in order to get free movement in our city.

TABLE I. DESIGN RESTRICTIONS

Aspect	***Feature***	***Value***	***Unit***
User	Average weight	38.9	kg
	Average height	1.48	m
	Minimum walking velocity	0.86	m/s
	Maximun walking velocity	1.57	m/s
environment	Minimum width of doors	0.90	m
	Minimum separation between doors	1.20	m
	Maximun ramp slope	12%	-
	Maximun riser of stairs	0.18	m
	Maximum slope between sidewalk and driveway	0.20	m

TABLE II. DESIGN REQUIREMENTS

Feature	***Symbol***	***Value***	***Unit***
Maximun width	-	0.80	m
Maximun length	-	1.00	m
Maximun ramp slope	θ	8.5°	-
Maximun riser	h	0.20	m
Average velocity	v_w	1.30	m/s
Maximun weight of user	W_u	40.0	kg

3.2 Design of the Triple-Delta and Triple-Star Wheel Mechanism

We considered some parameters for the design of the Triple-Delta wheel mechanism, based on local market products and the idea of decrease the mass of the wheelchair.

- Use of polyurethane foam wheels (R=100mm), because they are commonly used in manual wheelchairs.
- Use of chain transmission system, due to this kind of system is lighter than a gear one.
- Pinion radius "Rp" in the same axis with the wheels must be less than the radius (r=3cm) of the lateral plates of the mechanism structure.

Furthermore, it was necessary to analyze the geometric shape of the mechanism, because when the wheelchair have to pass over a step, there should be no interference between the mechanism and the step. In other words, it must be a space "e" between the delta cover and the corner of the step. In Fig. 1, the geometric parameters of the triple-wheel mechanism are shown. Each value in the figure was defined previously, except by the center distance "m" between wheels. Equation (1) express the variation of the space "e" as a function of the constant “m” and the position of the wheelcenter “y1” while the mechanism climb the step.

$$e = \frac{(R^2+(h-y_1)\left(R-\sqrt{m^2-(R+h-y_1)^2}\right))}{m} - r \qquad (1)$$

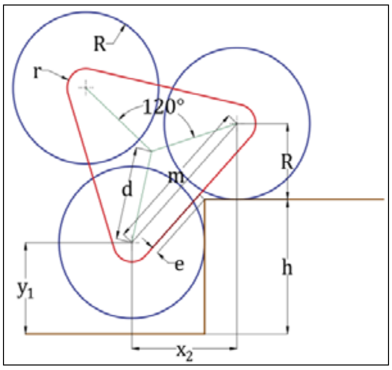

Figure 1. Triple-Delta wheel mechanism parameters

After doing various iterations with different values for “m”, we got a value, which keep the space “e” positive along the whole trajectory of the position “y_1”. Fig. 2 shows the relationship between “e” and “y_1” with the distance m=21.5 cm.

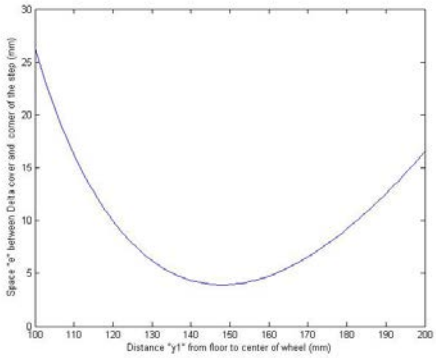

Figure 2. Distance “e” vs position “y1”

Once defined the value of “m”, we could start the development of the Triple-Star wheel mechanism. As can be seen in Fig. 3, we needed to calculate the length “L” of the mechanism and the radius “Rt” of the rear wheels. Due to the difference between the bearing for rear and frontal wheels, an uneven was originated (Oa=5cm) in the horizontal plane of their axis. So, in order to keep constant the distance between the axis of wheels, we selected wheels of radius Rt=9.5cm.

Figure 3. Schematic of structure to join Delta and Star mechanism

In a similar way to the Delta mechanism, we verified that the Star mechanism do not have interferences with the step while climbing. This verification was based on the equations show in [11], where we can confirm that the values of “L” y “Rt” were correct.

Finally, we designed both mechanism in a software CAD which included bearings, bolts, nuts and each specific component. Fig. 4 shows the final design of the Delta mechanism, Fig.5 illustrates how we distributed the chain transmission system and Fig. 6 shows the final design of the Star mechanism.

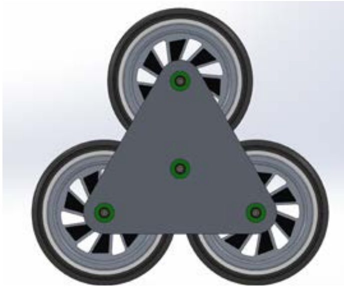

Figure 4. Triple-Delta mechanism

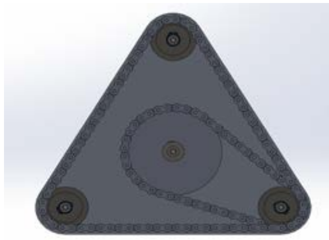

Figure 5. Chain system transmission of the Triple-Delta wheel mechanism

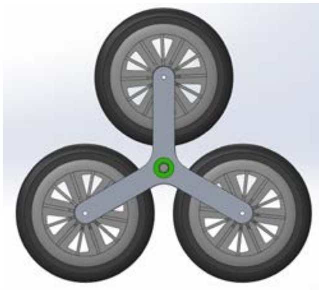

Figure 6. Triple-Star wheel mechanism

3.3 Selection of the motor

Table 3 shows the parameter considered to calculate the main features of the motor.

TABLE III. PARAMETERS FOR SELECTING THE MOTORS

Feature	*Symbol*	*Value*	*Unit*
Weight of user and chair	W_{uc}	440	N
Weight of batteries	W_{bat}	300	N
Weight of main structure	W_{st}	45	N
Weight of Triple-Delta mechanism	W_{sd}	30	N

Feature	***Symbol***	***Value***	***Unit***
Weight of motors	W_m	100	N
Weight of Triple-Star mechanism	W_{ss}	20	N
Weight of wheels	W_w	5	N
Rolling resistance coefficient	C_r	0.035	-
Maximum static frictional coefficient	μ_s	0.4	-

Equation (2) shows the torque needed in each of the four wheels in contact with the floor to move at a constant velocity on a ramp with the maximum slope (θ) considered in the design.

$$\tau_w = \frac{(Wuc+Wbat+2*Wsd+Wss+Wst)(\cos\theta*Cr+\sin\theta)*R}{4} \quad (2)$$

Replacing values in the equation, we got a torque of τ_w=4.9N.m. Then, multiplying this value with the desired angular velocity (ω_w=13.3rad/s) we got the power per wheel P_w=65.2W. Fig. 7 shows the schematic of the distribution of components in the delta mechanism and the Equation (3) shows how we calculated the total power for each motor. In this equation we included friction losses in the bearings (P_b) and factors design (f_{d1}=1.2 y f_{d2}=1.3) for the transmission in the simple and triple chain respectively.

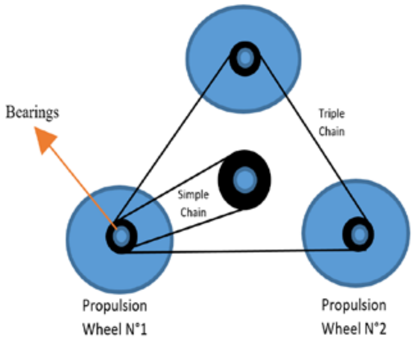

Figure 7. Schematic of the Delta Three-Wheel mechanism

$$P_m = f_{d1}*(f_{d2}*Pw+Pw)+P_b \quad (3)$$

Losses in bearing were calculated based on the manufacturer's manual [12], so the total power per motor was Pm=200W approximately. In addition, we chose a ratio (k=2.1) for the simple chain, in order to smooth the transition between advancing mode and climbing mode [11]. In this way, we got the nominal angular velocity ω_m=60 RPM and the torque τ_w=35N.m of th ve motor.

3.4 Weight distribution of wheelchair

We divided the wheelchair into three parts. The first part is the main structure, which support the chair and user, the second part is the Delta mechanism and the third part is the Star mechanism. We assumed that the position of the components in the first part (battery, user, etc.) keep constant while the wheelchair is moving or climbing. Thus, we had to define the right position of each component to allow to the Delta and Star mechanism climb the steps automatically.

Fig. 8 shows the FBD of the main structure before climb step and the FBD of the delta mechanism, where "T" is the motor torque to reach the climbing mode.

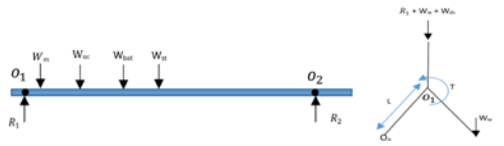

Figure 8. FBD Main structure and Delta-wheel mechanism

After many iterations, we got the appropriate positions to avoid a high torque. Based on the Newton's Laws of motion, que R_1=654N, R_2=231N and the torque T=40.4N.m. Although this torque is higher than the nominal motor torque, this peak is less than 120% so we decided to use it because this overstress will be use occasionally and for short periods.

Hence, we did a similar calculus for the rear wheels. Fig. 9 shows the FBD of the structure when the Delta mechanism is over the step, and the FBD of the Start mechanism in that position. In this case, F_1 is the force originated for the drag of frontal wheels.

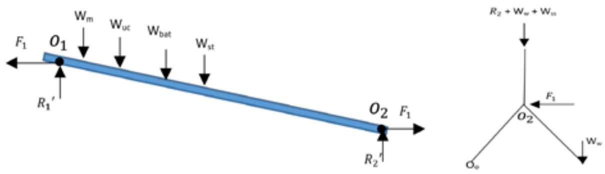

Figure 9. FBD Main structure and Star-wheel mechanism

From Newton's laws, we got that F_1=305N which is enough to reach the climbing mode. Nevertheless, this force must be less than the maximum frictional force between the wheels and the floor, as can be seen in Fig. 10, in order to avoid the wheel slip; thus, our system must accomplish Equation (4).

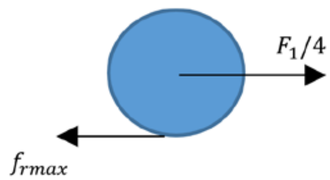

Figure 10. FBD of each frontal wheel in contact with the floor

$$f_{rmax} > F_1/4 \quad (4)$$

From Figure 8 we got R1'=787N, this reaction distributed between the four frontal wheels in contact with the floor and multiplied with the frictional coefficient μs gave us f_{rmax}=78.8N, which is more than F1/4 . In this way, we defined the position of each component in the structure of the wheelchair. Table 4 shows this position with respect to point O1.

TABLE IV. DISTANCE FROM COMPONENT TO O_1

Component	*Symbol*	*Distance*
Weight of user and chair	W_{uc}	10.5 cm
Weight of batteries	W_{bat}	19.0 cm
Weight of main structure	W_{st}	20.0 cm
Weight of motors	W_m	3.0 cm

3.5 CAD design of the wheelchair

We complete the design of the wheelchair by using a software CAD including each minimum component for the structure and mechanism. Besides, we distributed the components according to the distance calculated previously and considered as material the commercial steel A36. Fig. 11 shows the final design of the wheelchair, with two Delta mechanism and one Star mechanism and Fig. 12 illustrates the wheelchair with the cover for electric components. The general size of the wheelchair is less than the values specified in Table 2; in addition, we verified that the gravity center is inside the stability triangle of the wheelchair, so the wheelchair is safe to be controlled.

Figure 11. Design of wheelchair

Figure 12. Lateral view of wheelchair

3.6 Electronic Design

The main electronic components are the inertial sensors and the controller because we used both of them to determine the velocity and direction of the wheelchair.

We chose the inertial sensor MPU6050 [13] because it combines 3-axis accelerometers and 3-axis gyroscopes, which allowed us to determine the angles in the sagittal and frontal planes. This sensor uses I2C protocol [19] to send data from their inner registers to the controller. We used the MyRio [14] controller, product of National Instrument, for that reason the controller has tools to communicate through the I2C protocol, using LabView [20] as software for programming and a Wifi interface to program remotely the controller.

We developed a user interface to determine if the sensor works properly or if it is damaged. We used the self-test tool [15] of sensor to this purpose; if the self-test response do not exceed the limits of the datasheet, we can affirm that the sensor has passed the self-test. In other case, the part is deemed to have failed the self-test. The interface developed is shown in Fig. 13.

Figure 13. MPU configuration interface

As it was mentioned before, the MPU6050 sensor have an integrated gyroscope and accelerometer, both components are used to measure the inclination of the human body. We transform this data into speed and direction for the wheelchair, thus we eliminate the use of hands to control the wheelchair. The gyroscope measure angular velocity, which is transformed by Equation (5) into inclination. In a similar way, the accelerometer sends information about the distribution of gravity acceleration in the three main axes; this information is converted into inclination by Equation (6).

$$ø_{gxy}=ø_{xy0}+w_{xy}*\Delta T_{xy} \quad (5)$$

$$ø_{axy}=\text{atan}(a_{xy}/\sqrt{(a_{yx}^2+a_z^2)}). \quad (6)$$

where,

ϕ_{axy} = angle of inclination measured by accelerometer
ϕ_{gxy} = angle of inclination measured by gyroscope
ϕ_{xy0} = previous angle measured by gyroscope
w_{xy0} = angular velocity obtained by gyroscope
ΔT_{xy} = gyroscope sampling period
a_{xy} = acceleration on the x,y axis given by accelerometer
a_z = acceleration on axis z measured by accelerometer

Equation (6) is obtained by using rotation matrix in 3D frames, we used a passive rotation [16] instead of active rotation because the sensor give us the value of the three components of gravity in the rotated frame; so we can keep constant the gravity vector. The equation of the passive rotation matrix is shown in Equation (7), it correspond to the angles yaw, pitch, and roll [18], which are used frequently in aeronautics applications.

$$\begin{bmatrix} Px' \\ Py' \\ Pz' \end{bmatrix} = R^{T} * \begin{bmatrix} Px \\ Py \\ Pz \end{bmatrix} \quad (7)$$

where,

$$R = \begin{bmatrix} C\phi C\theta & C\phi S\theta S\psi - S\phi C\psi & C\phi S\theta C\psi + S\phi S\psi \\ S\phi C\theta & S\phi S\theta S\psi - C\phi C\psi & S\phi S\theta C\psi - S\phi S\psi \\ -S\theta & C\theta S\psi & C\theta C\psi \end{bmatrix}$$

And the angles θ, ψ and ϕ are taken based on Fig. 14.

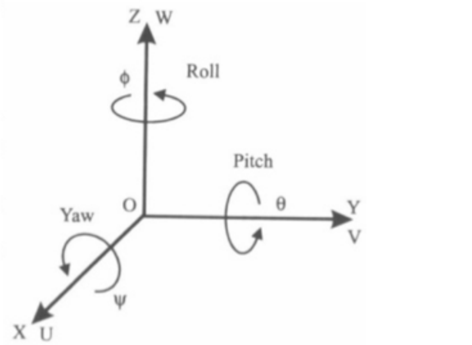

Figure 14. Yaw, pitch and roll angles

We passed the values obtained previously trough the complementary filter [17] to obtain a single inclination value filtered. This filter take data of the slow moving signals from the accelerometer and the fast moving signals from gyroscope to combine them in order to get a unique angle filtered. The complementary filter equation used can be seen in Equation (8).

$$\phi_{xy} = 0.97*(\phi_{xy0} + w_{xy}*\Delta T_{xy}) + 0.03*\phi_{axy} \quad (8)$$

Finally, we programmed a code in LabView to control the motors from the wheelchair by receiving information of the body inclination from the inertial sensors. A partial code can be seen in Fig. 15.

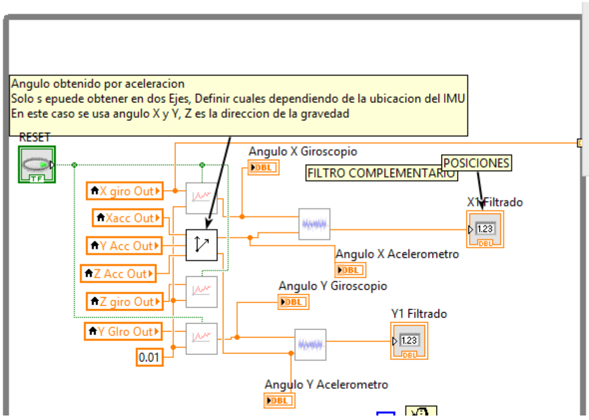

Figure 15. Partial code of the wheelchair control

4. WHEELCHAIR IMPLEMENTATION

At the moment of the presentation of this article, the implementation of the prototype has not been yet completed. In the mechanical area, the triple-wheel parts have been machined and fixed to the main wheelchair chassis. This means that most of the wheelchair prototype has been constructed as shown in Fig. 16; however, it is still pending to attach the user's chair to the structure. Furthermore, we placed the wheelchair on a ladder to verify that the geometric calculations were correct. As can be seen in Fig. 17, we did not detect interferences in the way to up or down stairs.

Figure 16. Structure of the wheelchair

Figure 17. Structure located on ladder

On the electronic part, we established communication between the IMU and the controller. Besides, we compared the angle measured by the gyroscopes, accelerometers and the complementary filter, as shown in Fig. 18. Thus, we could send this data to the motors power driver, achieving a correct control of their speeds and direction.

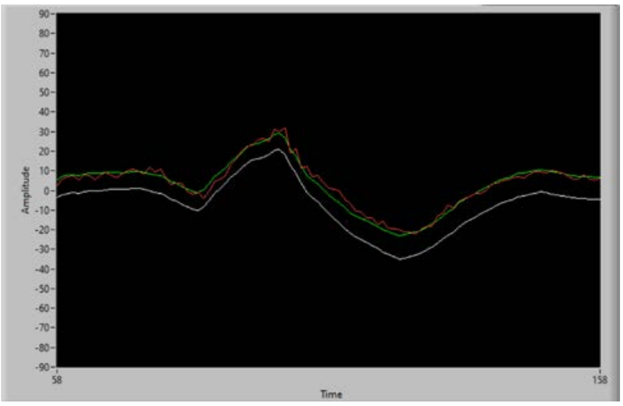

Figure 18. Inertial sensor data

5. RESULTS

Although we did not complete the implementation of the prototype, the partial tests carried out confirmed that main calculus were developed properly. On the mechanical area, we verified that the proposed triple-wheel mechanism and its union to the chassis is adequate, due to the chair has managed to go up and down on stairs without any interference.

On the electronic area, we got data from the inertial sensors and transformed this data into velocity and direction for the wheelchair. However, the coupling of the user's chair to the main structure is still pending. When we do that, we will prove that the motors were properly selected. In addition, we will install the inertial sensor in a way that can be easily added to the patient each time the chair is used.

The methodology proposed allowed us to design the mechanical part of the wheelchair and define the main parameters of its motors. By using geometric equations and Newton's laws, we achieve to design completely a wheelchair capable to climb steps and move without restriction in urban areas.

Although, the material considered in this design is steel A36, it could be possible to use aluminum or another lighter material in order to decrease the weight of the wheelchair and do not overcharge the motor while climbing steps. The electric and electronic part will be attached to the structure and protected by non-conducted material. The weight of this components is less than 1kg, so we decided to eliminate it from the calculus. Finally, although we considered the use of lead-acid batteries due to be cheap, we suggest the use of lithium batteries because it is safer electrically and there is not evaporating acid.

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