Design of a Prototype Mechatronic Wheelchair for People with Motor Disabilities

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Abstract
People with motor disabilities require some mechanism or technological solution to move around autonomously. The most common way is through a voice-controlled electromechanical chair; however, these solutions are expensive and often require expert support in training. This paper aims to design a low-cost and easy-to-use electromechanical chair that allows autonomous navigation controlled by an electronic interface, a joystick, and voice recognition. In the first step, modeling an electrical wheelchair prototype with 3D software is essential; subsequently, a voice command system to control wheelchair navigation is developed based on the speech recognition library of Python. Finally, an electronic interface is designed and integrated into an Arduino Mega embedded module to recognize the voice commands and control the wheelchair's mechanical system navigation. The results of this research are promising, considering the low cost of hardware design, the well-performance prototype, and the easy-to-use navigation system. The joystick control was accurate and gave four essential movements to the wheelchair; the voice recognition uses multi-tasking with threading algorithms to interpret and execute wheelchair navigation commands simultaneously. To enhance the prototype performance in future advances, optimizing the time response in command execution and setup system to individual user's requirements is recommendable.

Keywords
Electrical wheelchair, disabilities person, voice recognizing, threading programming

1. Introduction

Motor disability is a condition characterized by an individual's inability to independently engage in physical movement. Peru has a notable prevalence in this particular domain, and despite ongoing efforts towards the integration of individuals with disabilities, achieving this objective remains challenging within our societal context. The inclusion of individuals with disabilities in all economic activities is essential for promoting their independence. However, it is often observed that these individuals have challenges in securing employment due to their specific disability-related problems. According to the annual report of the Informatic and Statistic National Institute of Perú (INEI) in 2013, it was found that a total of 932 thousand individuals exhibit motor disabilities, which encompass challenges in mobility, ambulation, and the utilization of limbs [1]. According to a recent statistics analysis published by the National Institute of Statistics and Informatics (INEI) in 2019 [2], approximately 10% of the Peruvian population is affected by impairments. Among this group, 15.1% specifically experience motor disabilities, which corresponds to a total of 484,598 individuals facing challenges related to mobility and ambulation. The aforementioned publications provide an analysis of the various constraints experienced by individuals with disabilities, encompassing physical, occupational, social, and economic dimensions.

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In the academic literature, there has been significant emphasis placed on the investigation of electrical wheelchair navigation. As a result, numerous solutions have been proposed for controlling an electrical wheelchair through the integration of electronic interfaces with a joystick [3]. This particular control method relies on manual input through the use of hands. However, in cases where individuals are unable to move their arms or hands due to disabilities, alternative solutions based on signal processing are required. These solutions involve the utilization of bio-signals, which are generated from various parts of the human body. For instance, the bio-signal known as electro-oculography (EOG) can be produced through eye movement and can be obtained using a system consisting of an operational amplifier, an analog-to-digital converter (ADC), and a computer. This setup allows for the processing of the bio-signal and the transmission of commands to the wheelchair [4, 5, 6]. Another type of biological signal is the electroencephalogram (EEG), which originates from brain activity. However, the analysis and processing of this signal are highly intricate and necessitate the use of expensive equipment [7]. The electromyogram (EMG) is a cost-effective method for capturing bio-signals associated with muscle movements. However, its implementation necessitates the use of bio-amplifiers, analog-to-digital converters (ADCs), and computational resources for signal processing [7, 8]. Voice recognition technology has emerged as a highly promising solution for individuals with motor disabilities. To enable this functionality, the use of a headset and microphone is required to facilitate communication and issue commands to the wheelchair. In order to accurately interpret and respond to specific verbal instructions for wheelchair control, the integration of dedicated interpreter software and a microcontroller capable of processing voice signals is imperative [9, 10, 11, 3, 12, 13]. In conclusion, certain hybrid or dual approaches have been suggested in the form of voice and vision-based mechanisms [14] or head gesture recognition [15, 16]. Nevertheless, it should be noted that these solutions tend to be expensive and frequently necessitate the involvement of an expert to facilitate their utilization, upkeep, and instruction.

The objective of this study is to present a conceptual design for an electric wheelchair that can be controlled using both voice commands and a joystick. The inclusion of these dual control options is intended to assure the wheelchair's functionality in the event of voice command failure. In such a scenario, the joystick serves as a backup control mechanism, allowing the wheelchair to continue running seamlessly. The speech recognition library in Python is employed for voice recognition, while the Arduino Atmega embedded system is utilized for processing and recognizing voice commands. Additionally, the Arduino Atmega system is responsible for controlling the motor that enables the wheelchair's regulated navigation.

The present study is organized in the following manner: Section 2 provides a comprehensive account of the materials and methods employed in this study, encompassing the hardware design and software development aspects. Section 3 of the document provides an exposition of the experimental findings. Section 4 of the document encompasses the presentation of the conclusions and recommendations.

2. Material and method

2.1. Hardware Design

2.1.1. Structural design

The construction process of the wheelchair prototype commenced by implementing the measurements specified in the design. This involved cutting the pipes and subsequently joining them together using appropriate couplings. These steps were undertaken to create the foundation and subsequently the complete chassis of the prototype, with the aim of assuring its stability and symmetrical structure. Following this, drillings were conducted in order to install steel plates that were designed to give support for the motors and provide a level surface for their attachment using bolts and nuts. This process was carried out to ensure the structural soundness of the motor and to offer support for the primary axis of the tire. Subsequently, the front tires are affixed and calibrated in order to finalize the assembly of the chassis. In addition, an assessment is conducted on the state of the components, ensuring that they do not encounter any obstacles in the movement of the prototype.

The wheelchair operates by utilizing batteries that have been conditioned and are housed within a white box located underneath the seat. The strategic placement of the batteries contributes to maintaining the stability of the chair. The correctness of the wheelchair's design is demonstrated through the precise dimensions of its sections, weight support capabilities, and center of gravity. This particular prototype has been engineered to accommodate individuals weighing up to 70 kg. After the completion of the structural design, a series of paint layers are applied to enhance the aesthetic appearance of the chassis, resulting in the final appearance depicted in Figure 1.

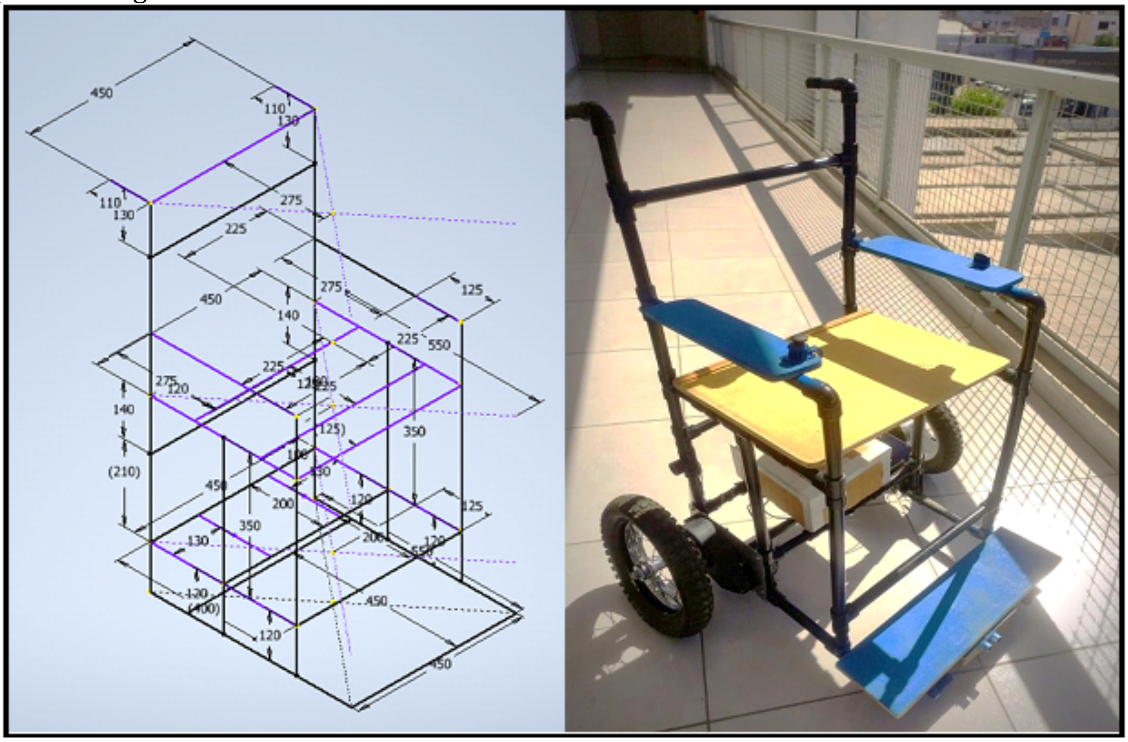

Figure 1: Design and completion of the wheelchair prototype's assembly

2.1.2. Electronic system

The electronic system comprises two power H-bridges, specifically the LM298n module, which incorporates buffers and enables the control of two motors. In our situation, these motors are responsible for controlling the left and right movements of the wheelchair. The control circuit is regulated by an Arduino embedded system, which incorporates an atmega328 microcontroller. This microcontroller, with its eight-bit architecture, possesses sufficient computational capabilities to effectively handle real-time data processing for our specific application. In order to access the voice recognition library in the cloud, it is necessary for the embedded system to establish an internet connection.

The system initiates the activation of two H-bridges to enable continuous control of the left and right motors. The movement of the wheelchair is determined by six fundamental commands, Table 1.

Table 1
Six voice commands

English	Spanish
Fordward	Avanza
Turn right	Derecha
Turn left	Izquierda
Backward	Retrocede
Fast	Rápido
Stop	Para

A pulse width modulation (PWM) signal is sent from the microprocessor to each H-bridge that controls the gearmotors and controls the speed motor as well, Figure 2. It works with the Echo and Trigger inputs, which are linked to Arduino pins 7 and 6.

Below is a list of the parts that were used in the system.

- 1 Arduino uno with 5v
- 1 LM298n H-bridge 5v
- 2 12v/730mA gearmotors with 4.2Nm of torque
- 1 ultrasound monitor with 5v
- 2 power inputs (5v to 12v, 20W)
- 1 microphone
- 1 headset

Python is needed to build the system, along with the speech recognition library and the algorithm to understand voice directions like "Avanza" for "Forward," "derecha" for "turn right," "izquierda" for "turn left," "Retrocede" for "backward," "Para" for "stop," and "Rápido" for "Fast."

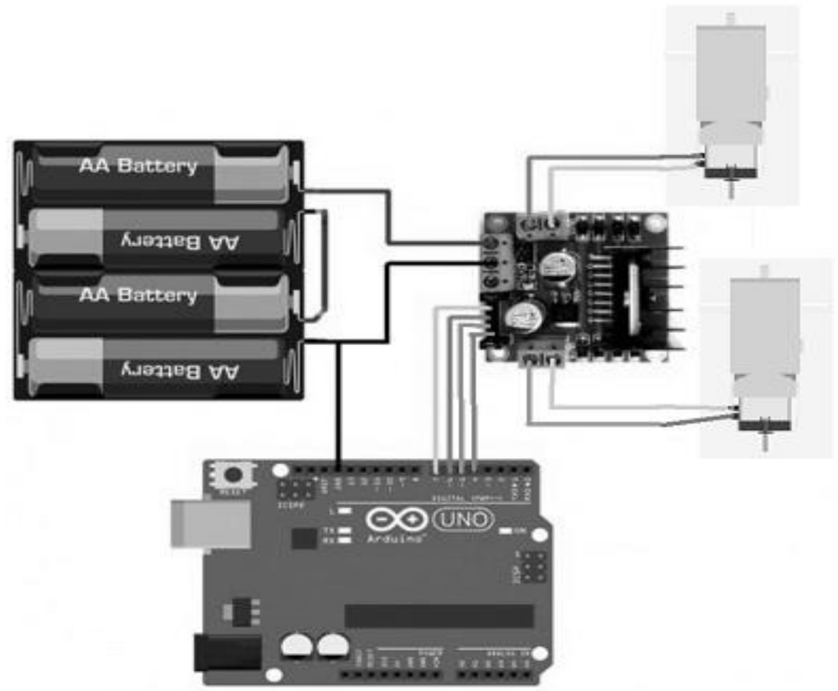

Figure 2: Arduino-H-bridge L298n two-gearmotor control (https://naylampmechatronics.com/)

2.1.3. Joystick control circuit

In order to operate the wheelchair using a joystick, a logical framework will be implemented, consisting of four distinct movements: forward, backward, left turn, and right turn. Each of these movements will be calibrated to accommodate pulse width modulation based on the degree of depression of the lever positioned at its center. To analyze this, we represent the range of joystick displacement for each movement on a Cartesian coordinate system. In order to make progress, we divide the Cartesian region into two zones: Zone "a" represents the left zone, which begins at 0, and Zone "b" represents the right zone, which ends at 1023. The range is measured in bits, taking into account the sensitivity of the analog-to-digital converter (ADC). In this particular case, the ADC has 10 bits, resulting in a range of [0-1023] bits, which is equivalent to a voltage range of [0-5] Volts. The center zone can be adjusted based on the joystick's sensitivity and individual requirements.

To facilitate the selection of the mode for joystick or voice command, a red button has been incorporated to enable the immediate choice of the desired operation mode by simply pressing the button.

2.2. Software design

2.2.1. Voice control

In order to facilitate navigation through voice commands, it is necessary to utilize the Python programming language along with the Speech Recognition library. Additionally, the following libraries are required: time, serial, pyttxs3, soundfile, and sounddevice. Similarly, it is imperative to assess the voice recognition service provided by Google for the Spanish language. To accomplish this, it is proposed to construct a comprehensive table that documents the outcomes of each command, categorizing them as either successful or erroneous. Additionally, the effectiveness of the system will be quantified by determining the percentage of successful commands. In brief, the algorithm will facilitate the evaluation of Spanish voice recognition by performing the following tasks:

An example of numbered list is as following.

1. Connect Arduino to a USB port.
2. Make a list of the directions that will be used to tell the actuators what to do through Arduino: ['forward', 'forward', 'forward', 'backward', 'retro', 'right', 'right', 'left', 'left', 'stop', 'anti', 'stop', 'stop', 'quickly']
3. A sample rate of 44100 Hz is set for recording a ".wav" file. That is, 44,100 pieces of sound will be recorded for every second. 44100 samples were picked because that's a common number for playing back audio and it's enough to get most of the details of the recording.
4. We set the time to "X" seconds to give the user more time to record in case the word gets longer and to take into account how long each Python command takes to run. A person's time for saying each order will help us figure out what "X" is worth.
5. With the previous settings, the audio is taken, and when it's done, a ".wav" file is made that will be overwritten over and over again.
6. The recorded sound will be cleaned of noise, and the recognition feature set to use the Google service and speak Spanish will be used.
7. The word that was recognized must be saved in a "command" variable. All words that were recognized will be made lowercase.
8. Any words that could have been recognized will be split up and the space between them will be taken out, leaving us with just the lowercase word.
9. The information that was gathered will be compared word by word until one fits a command that was set up.
10. After detecting the first spoken word, a signal will be sent to the Arduino through the serial port. The Arduino will read it and tell the H-bridge how to control the motors' rotation.
11. The last order that was spoken will be saved and work until a new command is spoken.
12. Inside the Arduino IDE, a bit will be set aside for each type of movement so that they can be controlled. In this case, "Forward" will be run if Python sends bit 1, "Backward" will be run if bit 2 is received, and so on. One problem with this way of moving the wheelchair is

that it throws off the user's timing with the recording. Because this was such a big problem, an algorithm was made that runs the listener in one thread and the orders in another. This way, the orders are carried out in the motors while the listener waits for new directions. In the same way, this new way of working lets us get the best response time from the motors to the controller's commands.

This is how the new program is put together.

1. Threading, a special library, is loaded so that the program can run in one or more processing threads.
2. The process of establishing serial communication with an Arduino device is initiated.
3. The aforementioned compilation of instructions is designated with a name.
4. Develop a function that encompasses the implementation of speech recognition and offers formatting capabilities for the transcribed words.
5. Furthermore, this function will specify the commands that are to be transmitted to the Arduino.
6. A new loop function is implemented with the sole purpose of actively monitoring and awaiting incoming commands within a specified time frame of 1.1 seconds.
7. The voice recognition feature is invoked to operate concurrently with the process of listening to incoming voice commands.

By employing this novel recognition technique, it is possible to guarantee a decrease in reading inaccuracies and enhance the efficiency of actuator reaction time.

2.3. Design of functional prototype

2.3.1. Wheelchair security

The proposed prototype will use a dual security system. To initiate the cancellation of a command, the user has the option to adjust the selector position. This action effectively halts the movement of the chair while transitioning between voice navigation mode and joystick navigation mode, or vice versa. Similarly, the prototype will incorporate ultrasonic sensors capable of detecting immediate obstructions at a range of less than 40 cm. This feature will enable the chair to halt its movement prior to any potential collision with an object. In this study, a total of 256 measurements were conducted using a specific sensor across several materials. The objective was to assess the potential inaccuracy in measurements at distances of 100 cm, 50 cm, and 40 cm in diverse materials, including concrete, cardboard, Medium Density Fiberboard (MDF), mirror plastic, and expanded polystyrene.

3. Results

3.1. Voice recognition

The experimentation involved conducting success and error tests with Google's speech recognition library, and the outcomes are presented in Table 2.

Table 2
Voice command hits and misses list

Command	Success	Error
“Avanza”	18 (90%)	2 (10%)
“Retrocede”	13 (65%)	7 (35%)
“Izquierda”	10 (50%)	10 (50%)
“Derecha”	18 (90%)	2 (10%)
“Para”	19 (95%)	1 (5%)
“Rapido”	20 (100%)	0 (0%)

Based on these data, it is possible to find out how effective each command is and how effective all commands are.

1. "Avanza": 18 hits were found out of 20 samples. It works 90% of the time when the order is given.
2. "Retrocede": Thirteen out of twenty samples gave right answers, which is a 35% error rate. Sometime this order wouldn't work in an emergency, which could hurt the person using it if the ultrasonic sensor emergency stop wasn't available. The order is changed to "retro," and the test is done again.
3. "Izquierda": Out of 20 samples, 10 had right answers, which means there was a 50% error. If we leave this command alone, it wouldn't be very useful in an emergency. But if the user types the same command more than twice and doesn't get an answer, they might think that the recognition isn't working and stop using this option. We change this command to "anti" (which means reverse) and run the test again.
4. "Derecha": 18 hits were found out of 20 samples. It works 90% of the time when the order is given.
5. "Para": Nineteen hits were found out of twenty samples. It works 95% of the time when the order is given.
6. "Rapido": Twenty samples were used, and twenty hits were found. It works every time that the order is given.
7. We'll now change "Izquierda" to "anti" and "Retrocede" to "retro" to get the result shown in Table 3.

Table 3
Recognizing commands after making changes

Retrocede	Retro	Izquierda	anti
13	19	10	17
65 %	95 %	50 %	85 %

We will add "anti" and "retro" as key commands for left turn and reverse after this test. This will also make it faster to say a command.

3.2. Voice command control

A novel software application was developed with the purpose of regulating the functioning of the motors. In order to supply power to the Arduino and the L298n, a power bank was employed. Similarly, it was linked to the computer system and initiated the issuance of commands, which were executed in accordance with anticipated outcomes. An issue that became apparent was the rather long recognition time of approximately 4 seconds for our initial code implementation. Table 4 displays the duration it takes for an individual to articulate each of the previously suggested instructions.

Table 4
Command recognizing delay

N	Avanza	Retrocede	Izquierda	Derecha	Para	Rápido
1	0.567	0.940	0.827	0.626	0.379	0.673
2	0.520	0.809	0.860	0.580	0.423	0.455
3	0.529	0.831	0.714	0.639	0.401	0.586
4	0.473	1.094	0.682	0.637	0.410	0.629
5	0.540	0.930	0.721	0.584	0.334	0.719
6	0.814	0.824	0.752	0.620	0.379	0.694
7	0.700	0.853	0.601	0.586	0.401	0.738

8	0.669	0.924	0.850	0.599	0.360	0.607
Mean	0.602	0.901	0.751	0.609	0.386	0.638

Consequently, a novel experiment was conducted utilizing the updated orders in order to enhance the time response. The outcomes of this experiment are outlined in Table 5, presented as follows:

Table 5
Command recognizing delay after change order

Retrocede	Retro	Izquierda	Anti
0.901	0.523	0.751	0.524

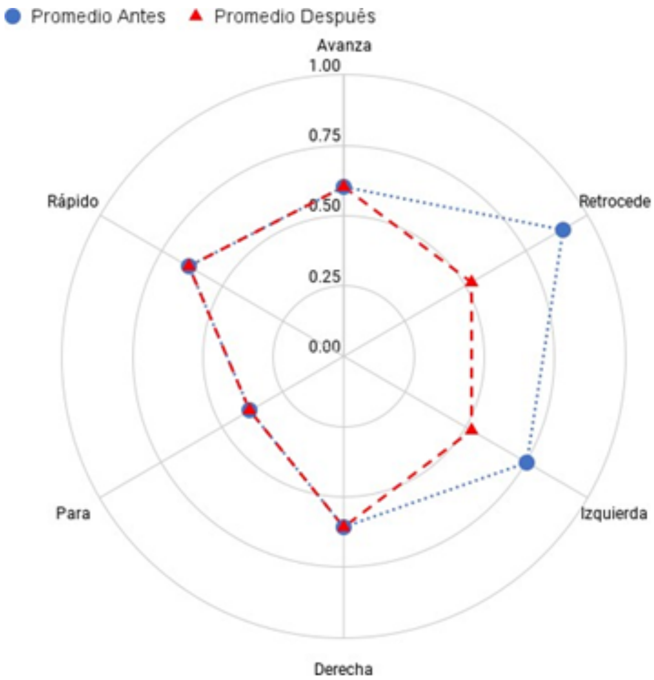

Figure 3: Time response in seconds before and after optimizing commands

Regarding the preceding instructions, we have obtained these novel findings with a reduced time interval. The new "anti" command for the "Izquierda" function offers enhanced precision and improved efficiency, resulting in reduced recording time.

3.3. Distance ultrasound sensor

In accordance with our established approach, an assessment was conducted to determine the precision of the HCSR-04 sensor when measuring various materials, including concrete, cardboard, MDF, mirror plastic, and technopor. The results of this evaluation are presented in Table 6.

In order to have a deeper comprehension of the data, an analysis was conducted on the dispersion pertaining to the mean. Hence, it is evident that the sensor exhibits a superior responsiveness when applied to concrete surfaces. However, when utilized with alternative materials such as mirror plastic and styrofoam, the signal may introduce inaccuracies in distance estimation. Hence, it is recommended that the wheelchair software control be modified to incorporate a joystick interface in order to enhance the navigation performance.

Table 6
Standard deviation of how far the HC-SR04 can measure

Material	Mean	Standard deviation
Concrete	100.0636	0.1236
Cardboard	100.0377	0.1880
MDF	99.6463	0.1874
Plastic	100.6274	0.4727
Technopor	99.9567	0.2714

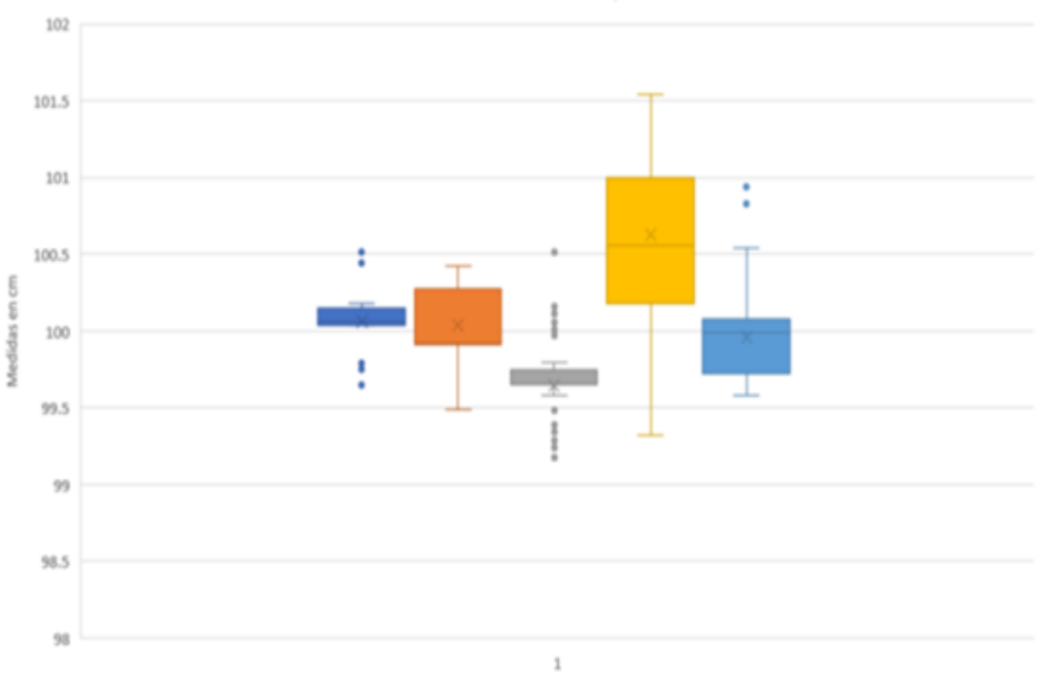

Figure 4: Data spread over a one-meter distance measured with the HC-SR04

As shown in Figure 4, the HSR-04 ultrasound sensor responds differently to different materials. Concrete gives more accurate readings, but there isn't much difference between the readings of other materials (a maximum standard deviation of 0.47 cm), so the system could keep the wheelchair moving.

3.4. Structural analysis

In the mechanical part, 3D software was used to do the structural analysis. This gave us useful information about how the chassis's structure would behave in different situations. In our models, we think that the chassis could have been made of PVC, aluminum, or steel tubes, with the same material used for the joints between the tubes.

During the simulations test, we look at the following features:

- A force of 9.81 m/s^2 of gravity
- The patient's weight limit is 40 kg
- The motor weighs 1 kg
- The battery weighs 3 kg
- The electrical parts weighs 1 kg

With these numbers, we'll start the simulations that go with them and show the results in terms of shrinkage, taking three things into account at the same time for this test.

1. PVC
2. Aluminum
3. Steel

We want to find the best material out of all of them to use as a base for cheaply putting together this type of wheelchair.

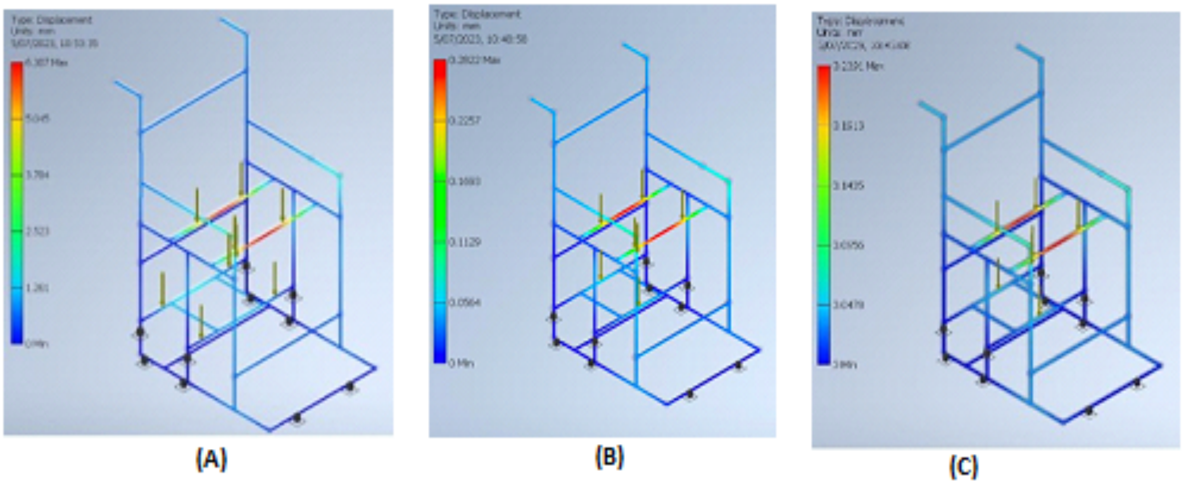

Figure 5: Analysis of structure in three materials: A) Steel B) Aluminum C) PVC

With these simulations, we can see that the deformation changes depending on the chassis's shape and the type of material used. Following these tests, the PVC frame has the most deformation, going up to a height of 6,307 mm. The next one is made of metal and is 0.282 mm thick. The last one is made of steel and is 0.239 mm thick. The displacement zone in all of these simulations is the same. It's in the area where the load acts directly (Table 7).

Table 7
Deformation in different materials

Material	Max. deformation (mm)
PVC	6.307
Aluminum	0.282
Steel	0.239

3.5. Power-Weight relationship

For a power of 350 and a weight of 45 kg, the power-to-weight ratio is 7.78, which can be seen by comparing the numbers to Table 8. Additionally, using the information in the same table, we can say that if we add more mass, the weight-to-power ratio will go down because the engine will have to make more power to make up for it.

Table 8
Relationship of power and weight

Power	45kg	50kg	55kg	60kg	65kg	70kg
120W	2.7	2.4	2.2	2	1.8	1.7
150W	3.3	3	2.7	2.5	2.3	2.1
180W	4	3.6	3.3	3	2.8	2.6
210W	4.7	4.2	3.8	3.5	3.2	3
240W	5.3	4.8	4.4	4	3.7	3.4
270W	6	5.4	4.9	4.5	4.1	3.8
300W	6.7	6	5.4	5	4.6	4.3

330W	7.3	6.6	6	5.5	5	4.7

4. Conclusions

In summary, we have successfully developed a mechatronics-based prototype wheelchair that incorporates essential features and is cost-effective. This design enables manual navigation using a joystick or automated navigation through voice commands issued by the user.

A cost-effective prototype of a wheelchair was developed using both computational modeling and physical construction, with the primary material being polyvinyl chloride (PVC). A comprehensive structural analysis was conducted on the prototype in order to validate its ability to endure the designated load, despite its relatively modest cost. Furthermore, the final iteration of the wheelchair prototype incorporated the installation of tires sourced from an authentic wheelchair, so enhancing its aesthetic appeal and lending it an authentic semblance.

The development of a control system that effectively coordinates the navigation of the prototype wheelchair has been successfully achieved. This system demonstrates adequacy, efficiency, and the potential for optimization. The implementation involved utilizing speech recognition and threading techniques. Python was employed as the programming language for voice command control, while the Arduino Software was utilized to facilitate the transmission and reception of instructions to the actuators.

Similarly, we have successfully enhanced the efficiency of voice command responses by reprogramming and organizing the available phrases or commands in a manner that ensures user comfort. In addition, it is possible to receive these words simultaneously with the transmission of commands to the actuators. Similarly, a delay of 1.1 seconds was achieved, resulting in an enhanced efficiency of our workflow that initially experienced a wait of 4 seconds between the execution of each order. Ultimately, we replaced the lexemes that exhibited the greatest temporal duration for directives that conveyed an identical directive, yet possessed enhanced efficiency in terms of articulation.

Ultimately, we have successfully integrated all the constituent stages or systems comprising the mechatronic wheelchair prototype in order to validate its functionality and enhance its efficiency. This phenomenon is evident in the outcomes gained and is demonstrated in the present research study.

5. Recommendations

Based on the findings of our research, we are able to offer the following advice for future endeavors.

- The prototype needs to be made from something other than PVC so that it can hold a person who weighs more than 50 kilograms. Aluminum may be a good choice because it is not more expensive than other materials and can hold more weight than PVC.
- Similarly, we suggest getting motors with more power that can move the suggested load through some kind of extra transmission. Online shops sell these, but they cost a lot more than the ones we used for this project.
- To use electronic control, we suggest making a PCB card with all the parts that will be used. In the same way, a Raspberry Pi or an ESP32 card can be used instead of an Arduino. This makes sending messages to the actuators faster. Also, we believe it would be more effective to use the VRM v3 Voice Recognition Module version 3. This module can recognize voice commands without an Internet connection, does not require a computer for signal processing, and lets you train up to seven commands.
- Finally, based on where the prototype will be used, we suggest adding more sensors to the area around the wheelchair to make the person using it safer.

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