Fuzzy Logic and Artificial Vision Application in a Lead-Acid Battery Charger for an Electric Wheelchair

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Abstract

Every day, people are becoming more concerned about the well-being of others and the inclusion of those who do not have the same physical capabilities to thrive in their daily lives or workplaces. Fifteen percent of the population suffers from locomotor disorders that affect muscles, tendons, ligaments, nerves, and can even impact bones. These disorders can be sudden or short-term in nature, preventing normal development for those affected. Lower back pain is one of the most common, with 568 million people suffering from it, leading to reduced social interaction, work difficulties, early retirement, and low levels of social well-being. This is a significant population to address, as four out of every ten are part of the economically active population. Therefore, focusing on alleviating the difficulties faced by this population in their daily lives, this study details the design and manufacturing of a motorized electric wheelchair prototype aimed at extending the lifespan of a lead-acid battery with a charger using fuzzy logic. Additionally, this device features a GPS system that allows for location tracking and sending an emergency SMS message in cases where the user cannot get back up and a Jetson Nano that runs YOLO model to artificial vision. All of this is aimed at providing greater autonomy and safety to this often overlooked population.

Keywords
Electric Wheelchair, IA, Fuzzy Logic, Battery Charger

1. Introduction
According to the World Health Organization (WHO), 1.71 billion people suffer from musculoskeletal disorders, and it is one of the main causes of disability in the world, where low back pain is one of the most frequent with 568 million people. who suffer from it. It is an important population to consider since they represent 2.17% of the total world population. The same ones that are restrictive of both the mobility, skill and autonomy of a person, which causes less capacity for social participation, as well as low levels of social well-being and early retirement since they face difficulties in the workplace than the prevents them from developing optimally, either due to not having the necessary tools or due to permanent social discrimination.

According to INEI, 15.1% of the total number of people in Peru with various disabilities have locomotive disorders, which is why they require the use of wheelchairs.

Electric wheelchairs have greater benefits than a conventional one, for example, they help people have greater autonomy, mobilization and movement. However, currently these chairs do not have a system that helps regulate battery use.

Therefore, this article presents the design and implementation of a motorized system that allows the control of the movement and direction of the wheelchair, as well as the regulation of the use of its batteries.

1.1 Objectives

- Develop an electric wheelchair that can improve the autonomy of people with motor disorders.
- Develop and manufacture a prototype of an electric wheelchair and a lead-acid battery charger that can be easily produced in the social context of Latin America.
- Determine the load and power supply of the charger and power consumption of the motors..

2. Literature Review

Analyzing the literature, various sources were obtained regarding the technology applied in electric wheelchairs. Freitas et al. (2017) implemented the development of a Mamdani fuzzy logic control that enables the control of the DC motor speed based on an Arduino system, resulting in precise rotation speed with minimal overshoot or insufficient parameters according to the prototype's needs. This proposal is characterized by the ease of molding the Mamdani Fuzzy Logic control system as it is intuitive, adapts quickly, and does not require complex mathematical logic.

Gaibor et al. (2018) designed and implemented a fuzzy controller for the Inteco brand pendulum car system in inverted pendulum mode. The controller design was based on the mathematical simulation model, applying two fuzzy controls, one for pendulum position and the other for the car. Tibaduiza et al. (2011) implemented fuzzy logic control for position control of each joint (direct kinematics) in a PUMA-type robotic manipulator. The fuzzy toolbox of Matlab was used for demonstration, and the implementation was done in a PLC, resulting in smoother movements with lower current peaks.

Ramirez et al. (2013) developed a linear position control system for a mobile platform using fuzzy logic. The platform was assigned an initial value with a specific distance that needed to be maintained automatically. Agredo (2011) implemented speed control of a DC motor using fuzzy logic in the Labview platform, demonstrating minimal computational requirements and the viability of replacing existing controllers with intelligent control systems.

Barber et al. (2013) conducted control experiments using Simulink with Arduino as low-cost hardware, connecting Simulink to a real system for laboratory practices at Carlos III University of Madrid. Valero Eduardo (2014) implemented a system in a pool using Arduino Mega 2560 with various sensors for temperature, ultrasound, infrared, pH, and an LCD, controlling water temperature, purifier, and pool lighting through on-off and PID control.

Mayta et al. (2018) analyzed and compared PID and fuzzy PID controllers using LabVIEW for water level control in a control and automation laboratory. Flores et al. (2017) developed a fuzzy control system for monitoring temperature, humidity, pH, and electrical conductivity in ornamental plant greenhouses, achieving rapid responses compared to traditional methods.

Avilés (2018) designed a circuit for monitoring and implemented fuzzy temperature control for an incubator using a microcontroller and a digital temperature sensor. Cárdenas et al. (2018) compared PID, fuzzy, and predictive control algorithms applied to solar tracking systems using photovoltaic panels. Rada (2018) collected library information on FuzzyLite for fuzzy logic control, emphasizing the precision and documentation of FuzzyLite compared to other libraries.

Espitia et al. (2009) designed and simulated a fuzzy controller for a DC motor based on Boolean relationships, improving control systems based on Boolean logic. Regarding fuzzy sets, an overlap was employed to achieve smooth control transitions.

On another note, Jian, M. et al. (2022) used various versions of the YOLO model to efficiently detect cracks in the wood of ancient structures, with YOLO v4s-mish being the best option. Dandang, W., and Dongjian, H. (2021) conducted a study with YOLO v5s to identify apple fruitlets early in their development for early yield estimation and automatic thinning, achieving a recall rate of 87.6% and a precision of 95.8%.

3. Methods

3.1 Prototyping and 3D printing

First, a scaled prototype was created to test the differential wheel and rotation programming logic on the same axis. This prototype was based on an electric cart used in the laboratories of the University of Lima to teach students the basic concepts of Arduino programming.

Similarly, the design of the battery charger case began by using a square box as a base, which underwent various iterations until the chosen design was finalized.

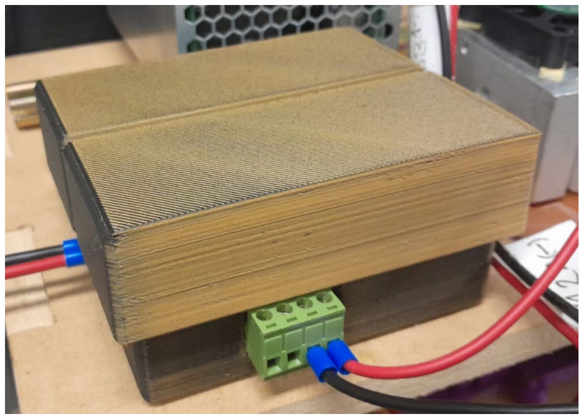

Figure 1. Final design of the fuzzy logic board case

Once the programming logic was confirmed, the electrical and electronic schematic of the final product was created to initiate the manufacturing process.

3.2 Mechanical Design and construction

For the construction process, it was necessary to manufacture metal supports for the 24-volt batteries, clamps, motor mounts, and the wheel supports. These parts were fabricated using manual tools such as saws, clamps, a bench press, hammer, and, for bending the metal bars that serve as clamps, a metal tube and a point of support were used to achieve the desired shape.

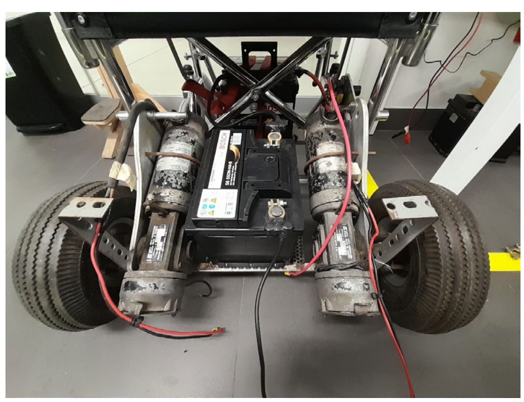

Figure 2. Motors mounted on the wheelchair

Similarly, the rear wheels of the wheelchair were replaced with a pair of rubber tires with rims. This was done to enhance rear traction, provide better shock absorption on uneven terrain, and reduce vibrations that may cause discomfort to the user.

Figure 3. Rubber wheels of the wheelchair

Finally, 3D printing was employed for the rails that support the electronic components situated above the batteries. For these parts, a modified Ender 5 3D printer with Klipper firmware and PLA plastic was used.

3.3 Electric system

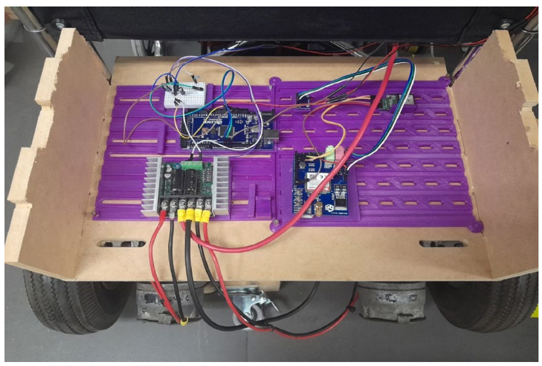

Figure 4. Electronics for wheel control and sensors

As a power source, two 12-volt 55-ampere lead-acid car batteries were used, connected in series to provide a total of 24 volts. The choice of these batteries was made due to their high availability in the social context of various countries where it might be more challenging to find lithium batteries.

To drive the wheels, two DC motors of model MVA M34D and brand Leroy Somer were used. These two motors were recycled from old machines, aligning with the idea of being able to manufacture this prototype in areas with relatively limited resources.

Figure 5. DC motor with its corresponding rubber wheel

3.4 Electronic and control system

First, we have steering control. For this project, a joystick was chosen as the control module due to its ease of understanding and minimal physical effort required. In this case, the joystick provides analog data ranging from 0 to 1023, which is then processed to obtain a float value between -1.0 and 1.0 on both axes. This value can be interpreted as a vector originating from the origin of the Cartesian plane, capable of any angle and modulus within a canonical circumference.

However, these values are not obtained linearly using the Arduino map() function. Instead, for better power control, the value output by the peripheral is squared after being parameterized between -1 and 1 using a custom function called mapExp(). The result of this operation is that with minimal joystick movement, the motors hardly move, and to achieve higher speeds, the user must move the joystick to values close to 1. This translates to more precise control at low values and more responsive control at high values.

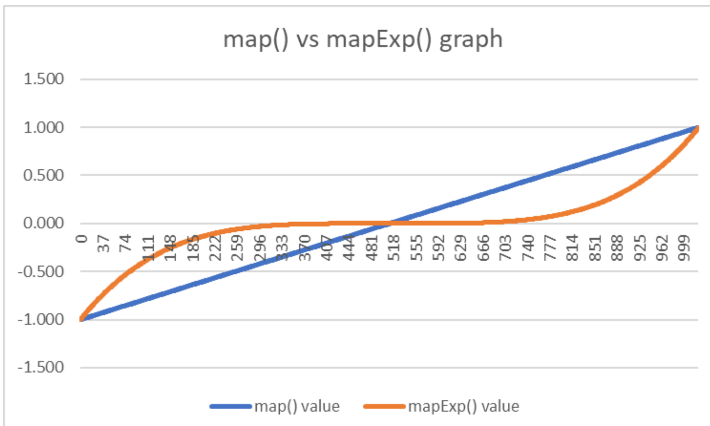

Figure 6. Graph comparing values of Map() and MapExp()

The value generated by this function is subsequently translated into a value between 0 and 255, which are the values accepted by the SaberTooth driver for operation. In this range, 0 to 126 makes the motors turn in one direction, and 128 to 255 in the opposite direction, with 127 being the value for stopping the motors.

Next, utilizing the y-axis component of the mentioned vector (referred to as linear velocity) and the x-axis component (referred to as angular velocity), voltage is applied to the DC motors:

If the y-axis component is close to 0 and the x-axis component is different from 0, then the wheelchair rotates around its own axis in the direction indicated by the x-component (negative for left, positive for right).
If the y-axis component is not close to 0, then both motors turn in the same direction with a determined linear velocity, and the angular velocity value is subtracted from the wheel where differential turning is desired (negative for left, positive for right).

Secondly, we have the battery charger control. The charger consists of three important parts: the power source, the voltage regulator, and the fuzzy logic board with its corresponding Arduino UNO. The power source is a 24-volt and max 480 watts unit that connects to the 220-volt household electrical network with a three-phase cable. Additionally, the voltage regulator is responsible for reducing the voltage from the power source to 18 volts and 12 volts using an L7818CV and L7812CV MOSFET to power the fuzzy logic board and a pair of fans that cool part of the system. Finally, the board using fuzzy logic, whose electrical schematic and PCB design are shown below:

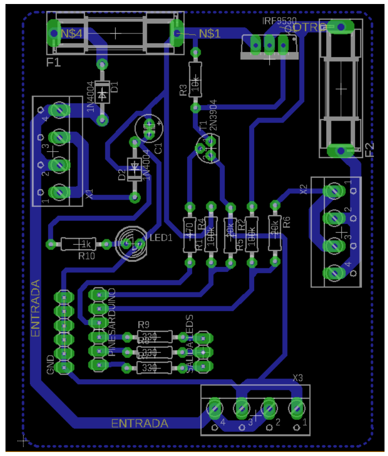

Figure 7. Electronic schematic of the fuzzy logic board.

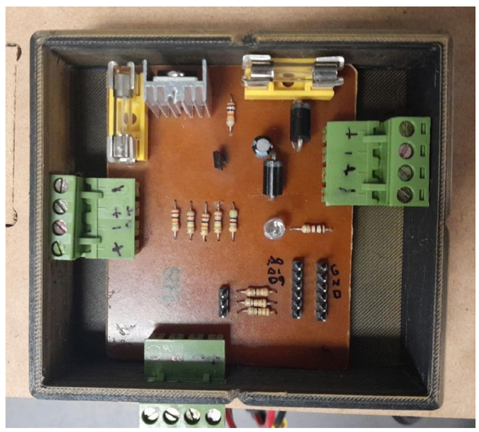

Figure 8. Fuzzy logic board

This system consists of a temperature sensor and a voltage sensor, both managed by an Arduino UNO. The data provided by these sensors are processed in the Arduino using fuzzy logic to adjust the time that the charger supplied voltage to the battery and the frequency of PWM signal to supply to the PCB. The logic is as follows:

If the battery has a voltage considered "low," the charger supplies voltage for a certain period or until the temperature condition is met. This condition states that if the battery reaches a temperature of 60 degrees Celsius, the power supply is cut off until it returns to normal levels.

If the power supply cycle concludes, a new voltage measurement is taken. If it is still considered "low," the process is restarted; otherwise, the device stops charging the battery.

On the other hand, if the battery is at a very low temperature (we consider low temperature at -10 degrees Celsius), such as the climatic conditions in the Peruvian highlands, it is not advisable to charge them abruptly because the sudden temperature change could reduce their lifespan. Therefore, if the sensor detects low temperatures, it regulates the PWM to start charging the batteries with low voltages.

The statements and membership functions of fuzzy logic will be further explored in the Programming section.

In third place, we have computer vision. For this prototype, it was decided to equip the wheelchair with a camera and a Jetson Nano, where an image recognition model called YOLO (You Only Look Once) is running. YOLO is capable of detecting a wide variety of objects and people.

For the implementation of this module, a different distribution of Ubuntu was used compared to the one provided by the NVIDIA manufacturer, called PyImageSearch. This Ubuntu operating system image comes with a large number of pre-installed libraries for the development and implementation of artificial intelligence focused on image recognition. For this prototype, both the screen and the Jetson Nano were powered by an external source connected to the domestic electrical grid.

To conclude this section, the wheel control system is composed of an Elegoo brand Arduino Mega2560 and a SaberTooth 25 x 2 V2 motor driver capable of handling the load of both DC motors and receiving voltage from the batteries, as it can reach peaks of 50 amperes for short periods of time.

Originally, the plan was to control the driver with a PWM signal from the Arduino Mega. However, as was confirmed in practice, the driver (originally designed to work with analog signals) is quite sensitive to this type of signal. Therefore, the use of PWM resulted in an uncontrollable motor and deficient torque. Because of this, a 1K-ohm and 10-microfarad R/C filter was implemented to smooth the signal from the Arduino. The oscilloscope images below illustrate the before and after effects of using the mentioned filter:

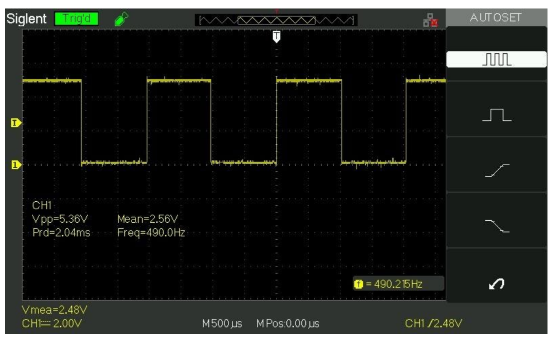

Figure 9. PWM signal from Arduino to Sabertooth 2x25 v2 Driver without R/C filter.

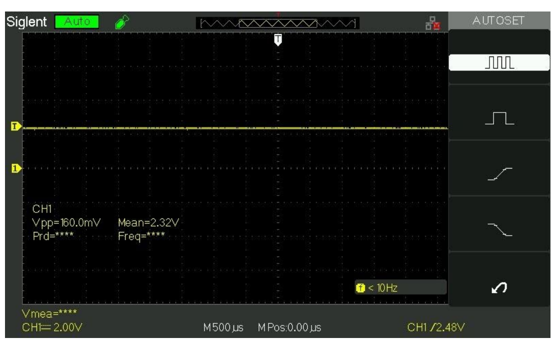

Figure 10. PWM signal from Arduino to Sabertooth 2x25 v2 Driver with R/C filter.

In the previous images, you can appreciate how the R/C filters are capable of taking a PWM signal, which, on average, is measured as a signal of 2.5 volts but not continuous, and conditioning it to actually be a continuous signal at that voltage. This is to prevent the driver from reading the high and low signals of the PWM and not behaving in the desired manner.

3.5 Programming

The prototype features various modules, including a gyroscope-accelerometer GY521, a voltage regulator (reducing from 24 to 4 volts to use the Arduino Uno's analog input as a voltage reader), TinyGPS for GPS functionality, a SIM card module (SIM800F model), a Jetson Nano, a rear camera connected to a front display, and the fuzzy logic board. All of these modules are connected to one of the three Arduino UNO boards, which act as central hubs along with the Jetson.

In the case of the gyroscope-accelerometer, GPS G229, and the SIM card, they are used to assist the wheelchair user in cases of accidents where the user cannot get up on their own. When the gyroscope-accelerometer registers an angle greater than 60 degrees in any of its axes, the SIM card module will send an SMS message to a predetermined emergency number, including the coordinates and time of the accident where the wheelchair has tipped over.

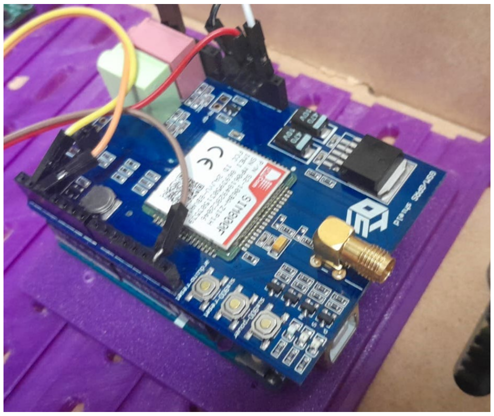

Figure 11. Arduino UNO with Shield SIM800F

Figure 12. GPS G229

Figure 13. Sensor accelerometer-gyroscope GY 521

On the other hand, for the control of the fuzzy logic board, the sensor LM35 was used as a temperature reader for the batteries, as well as for the voltage regulator to determine the state of charge of the lead-acid battery. Using the FuzzyLib library, the following membership functions for input and output variables were formulated:

```
FuzzySet*mf1 = new FuzzySet(-4.03,-2.641, -2.253, -1.536);
error->addFuzzySet(mf1);

FuzzySet*mf2 = new FuzzySet(-1.699, -0.7951, -0.4133, 0.1361);
error->addFuzzySet(mf2);

FuzzySet*mf3 = new FuzzySet(-1.21, -0.162, 0.08173, 1.073);
error->addFuzzySet(mf3);

FuzzySet*mf4 = new FuzzySet(0.247, 0.865, 1.125, 2.945);
error->addFuzzySet(mf4);
```

Figure 14. Membership functions of input values

```
FuzzySet*mfs1 = new FuzzySet(-121, -53.46, -36.26, 32.64);
potencia->addFuzzySet(mfs1);

FuzzySet*mfs2 = new FuzzySet(17.75, 85.85, 101.8, 171.8);
potencia->addFuzzySet(mfs2);

FuzzySet*mfs3 = new FuzzySet(105.3, 171.3, 189.3, 255.3);
potencia->addFuzzySet(mfs3);

FuzzySet*mfs4 = new FuzzySet(179, 227, 241, 306);
potencia->addFuzzySet(mfs4);
```

Figure 15. Membership functions of output values

This fuzzy control is responsible for obtaining voltage and temperature data to determine a PWM signal for charging the batteries, based on the logic explained in previous chapters.

Regarding the rear camera, front display, and Jetson Nano, they are used for real-time detection of objects and people through the use of Artificial Intelligence. The Jetson Nano runs an Ubuntu distribution provided by the manufacturer (NVIDIA) as its operating system. A Python 3 file was programmed using UltraLytics, OpenCV, and Supervision libraries for the detection of people and objects. The purpose of this system is to provide a broader view for the user, as sitting in a wheelchair restricts the field of vision since the torso cannot freely move to complement neck movement (assuming the user is capable of moving their neck).

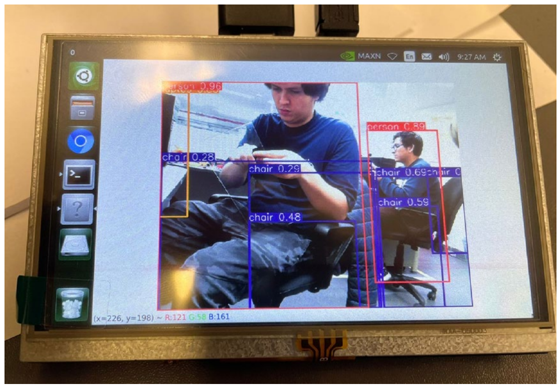

Figure 16. YOLO model image recognizing a group of laboratory workers.

In the previous image, you can appreciate how the YOLO model is capable of detecting and indicating various objects and people with a square through the camera. This model is even capable of adding a label with the name of the object it is detecting and the probability that it is indeed what is indicated in the label.

4. Results and Discussion

Once the wheel control system was completed, the energy consumption was measured using an ammeter. The wheelchair was tested in three different scenarios: a scenario without a load, a scenario with a 64 kg load, and a scenario with a 64 kg load on an inclined surface. The measurements yielded average currents of 5.04 amps, 12.3 amps, and 21.8 amps in each scenario, corresponding to 120.96 watts, 295.2 watts, and 523.2 watts, respectively.

On the other hand, in the image recognition section, an average preprocessing time of 7.1 ms, an inference time of 6565 ms, and a postprocessing time of 4.12 ms were obtained. The inference time strongly contrasts with the results obtained by Jian, M. et al. in their work "Complex Texture Contour Feature Extraction of Cracks in Timber Structures of Ancient Architecture Based on YOLO Algorithm," where they had an inference time of only 21 ms. The cause of this discrepancy has not yet been determined. However, as expected, it was also observed that the YOLO image recognition model could detect objects such as chairs, tables, bags, and people with over 95% accuracy.

Finally, in the battery charger section, a measurement similar to that made with the motors was conducted. The result showed that it is capable of delivering a charging power of 126 watts. Furthermore, overheating of the battery was successfully avoided by employing PWM to regulate the voltage based on its temperature. This measure was implemented to prevent both battery overheating and a reduction in battery lifespan due to sudden charging at low temperatures.

4.1 Proposed Improvements

The proposal to conduct a small ergonomics study and design an adjustable backrest for lumbar and cervical support, based on a conventional wheelchair, is an excellent idea. This approach would not only enhance the comfort of the wheelchair but also address potential health issues related to pressure and temperature in specific areas of the body during extended periods, such as preventing pressure ulcers, fungal infections, and possibly mitigating the risk of developing poor postures in users. Integrating ergonomic considerations into the design could have a significant impact on the long-term quality of life and health of wheelchair users.

Additionally, it is recommended to conduct a thorough study of both the operating system and the code used to implement computer vision using the YOLO model. This would enhance the image processing speed. Likewise, consideration could be given to replacing the Jetson Nano with another Nvidia model, such as the Jetson TX2 with 4 GB of RAM.

5. Conclusion

In summary, the prototype demonstrated its ability to facilitate the mechanical task performed by a user of conventional wheelchairs by successfully moving not only a person weighing 64 kg but also the weight of the wheelchair itself with all the electrical and electronic modules it contains. Therefore, it is concluded that this prototype is indeed capable of easing the effort of individuals with motor problems with the simple movement of a joystick, in addition to allowing the user to have a more comprehensive view of their surroundings by being able to look backward. Additionally, it provides the assistance of an AI to identify objects that the user might not initially notice.

Furthermore, except for the use of the Jetson Nano, the manufacturing of the wheelchair prototype was achieved without the need for high-tech manufacturing equipment such as CNC lathes and without requiring components that are hard to find in the Latin American and Peruvian context. In conclusion, as of the progress date of this project, the manufacturing of the wheelchair prototype is technically feasible in places with limited access to materials, equipment, and digital manufacturing knowledge.

Finally, regarding battery charging, fuzzy logic succeeded in maintaining a constant temperature for the batteries through the PWM delivered by the fuzzy logic. In conclusion, the fuzzy charger optimally charges the batteries.
Furthermore, it was determined that the charger is capable of delivering a maximum of 7 amperes and 126 watts of power to charge the batteries. Additionally, it was determined that the maximum consumption per motor is 523.2 watts, which is within the capabilities of the 12-volt, 55-ampere batteries connected in series.

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