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Original Article

Implementation of a Low-Cost Steering Control System for a Wheelchair based on Electrooculography Signals

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Abstract - *This study presents the development of a low-cost steering control for a wheelchair powered by eye movements using electrooculography (EOG) signals. The main objective was to allow people with severe motor disabilities who cannot afford expensive electric wheelchairs to control the movement of a wheelchair intuitively and efficiently using only the movements of their eyes. This work comprised several stages, including designing the EOG signal acquisition system, preprocessing, and implementing a control algorithm to classify human eye movements and determine the desired direction for the wheelchair. This work seeks to position a more accessible option in the field of mobile assistance for people with motor disabilities by providing an intuitive control system for the movement of a wheelchair. The steering tests were successful and demonstrated the system's ability to identify and respond appropriately to the orientation desired by the user, reaching an overall effectiveness of 92% with high rates of precision achieved in the subtests where the direction where the user wanted to steer the wheelchair (forwards, backwards, right and left) was evaluated. The results encourage future research and development in this area, intending to improve to some extent the independence and quality of life of people with disabilities through innovative and adaptive assistive technologies. In summary, this study contributes to the advancement of assistive technology and opens new possibilities for more inclusive and autonomous mobility*.

Keywords - *Electrooculography (EOG) signals, Signals classification, Steering control, Wheelchair, Eye movements.*

1. Introduction

The Pan American Health Organization (PAHO) defines disability as physical, mental, intellectual, or sensory system limitations of the human body that, in communion with the barriers and non-inclusion of our society, hinder a more functional and adaptive development of those who carry a disability [1]. According to the 2017 National Institute of Statistics and Informatics (INEI) report, in Peru, 10.3% of people have some type of disability [2]. Within this group are people who are paraplegics or quadriplegics; they have a deficiency in their motor systems due to the loss of the ability to move the body and/or also the loss of any sensation due to the damage produced in their Central Nervous System (CNS). These conditions involve complete or partial paralysis of the trunk and extremities. Due to this reason, it is necessary to understand what type of disability occurs based on the degree of severity. Paraplegia is characterized by losing control of movement in the lower extremities. At the same time, tetraplegia, or quadriplegia, can cause a decrease in general mobility and loss of total control of the extremities (upper and lower). In the case of quadriplegia, the main cause is an injury to the spinal cord as a result of an accident, a blow with a fracture to the spinal column, a cut or perforation with some type of weapon, which causes the Central Nervous System (CNS) to lose functionality to receive and respond fully to the body's stimuli. This occurs because the signals that control muscle movement that should be transported through the spinal tract are inhibited. Hence, the motor function of the entire body is disabled. If the injury is very serious, the person may be deprived of the ability to speak, leaving only the brain and the movements of the human eye as channels of communication and control [3].

Various investigations have addressed the problems in the motor functions of the body. In a study about the control of a wheelchair using Electrooculography (EOG) signals in real-time, the development and evaluation of a wheelchair control system in real-time was presented [4]. The objective of that work was to investigate a control approach based on modes of interaction, and a dataset was used to evaluate the system performance. Another investigation studied a control method that included preprocessing and processing signal stages [5]. Additionally, a machine learning model for classifying the different types of eye movements was used, thus making this an intelligent steering control system. A similar study developed a convolutional neural network to classify the direction of the motion [6]; in this case, a camera was used to catch the movement of the eyes.

Regarding the development of wearable devices to implement the steering control of a wheelchair, a study presented an algorithm to detect eye movements, such as smooth tracking, blinks, and retinal fixations, using a wearable device [7]. The study included naturalistic data collection and isolation of each movement to extract basic features, and k-nearest neighbors (KNN) classification was used to discriminate the movements. The results showed that blurs were easy to discriminate with basic features, while smooth tracks and vestibulo-ocular reflex (VORs) required additional feature extraction and analysis. The authors suggested that future work should include comparing filtering methods, a larger set of features to analyze and select with a feature selection algorithm, and results from various classification algorithms. In view of the above, this study proposes the use of movements of the eyes to steer a wheelchair, thus offering an innovative and low-cost solution that aims to improve the mobility of people with quadriplegia. EOG signals generated through the capture of eye movement will be used to determine in which direction the wheelchair goes.

2. Methodology

To develop the proposed steering control system for a wheelchair, we divided the work into three parts (Figure 1): First, the EOG signals were obtained; second, signal pre-processing was carried out; third and finally, the directional control design was carried out.

2.1. EOG Signals Acquisition

The first stage of the design captures the signals produced by the muscles during the movement of the human eye and records them with sufficient quality for subsequent processing. To do this, Zoll ECG adult electrodes were used, and the region of the location around the eyes was determined (Figure 2).

In addition, connectors that diverted the signals to an input amplifier were added. During this stage, it is essential to ensure that the study subject remains still relaxed and that appropriate protocols are followed. Next, the configuration of the signal amplifier was followed, including selecting the gain and low-pass filter to eliminate unwanted noise. Next, the signals were generated, recording the movements of the eyes. Finally, it must be considered that the waves obtained from muscle movement are weak; hence, electromagnetic interference or environmental noise affecting the signal quality must be avoided [8].

2.2. Signal Preprocessing

The second stage involves processing the acquired signals to improve their quality, which is carried out by eliminating signal noise produced by external agents. In this work, the preprocessing technique used was based on preamplification, filtering (high-pass and low-pass), postamplification and offset.

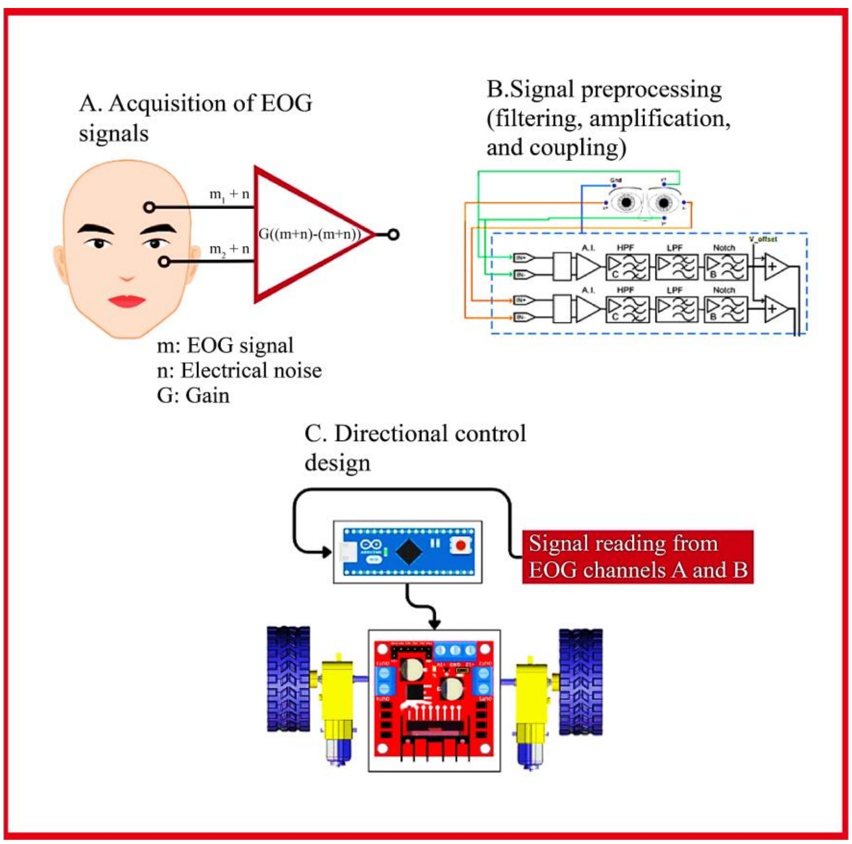

Fig. 1 Applied design to the proposed steering control system

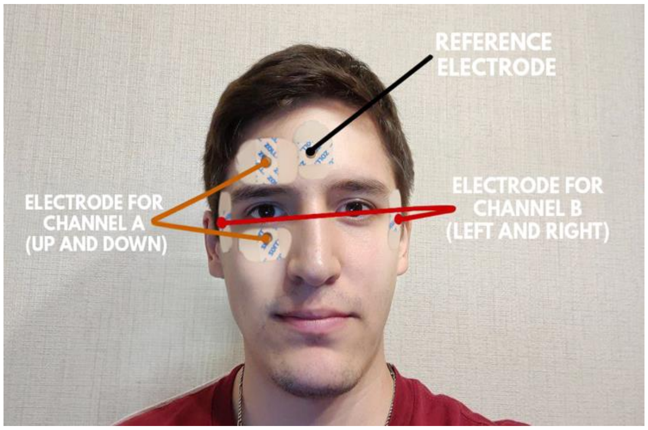

Fig. 2 Zoll ECG electrode location

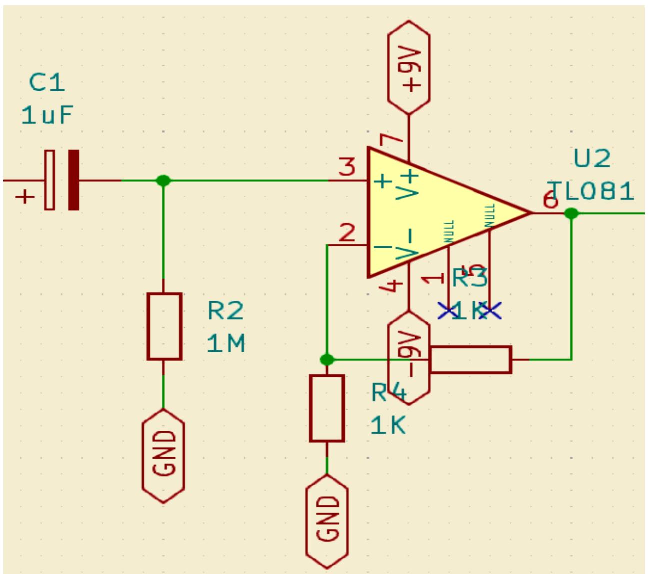

Fig. 3 High-pass filter design

Preamplification

A high-accuracy amplifier, AD620, was used to amplify the weak signals received by the electrodes. Its main function is to increase the amplitude of the input signal and filter its noise.

High-Pass Filter

The cutoff frequency used for this filter was 0.2Hz, which attenuates or eliminates frequencies below the mentioned value. The objective is to eliminate the Direct Current (DC) component and unwanted low frequencies present in the signals obtained from eye movements. In Figure 3, the basic circuit of this filter is presented.

To obtain the cutoff frequency of 0.2Hz, Equation 1 was used. The value of the resistor R_2 is equal to 1MΩ, and the value of the capacitor C_1 is 1μF.

$$f_c = \frac{1}{2\pi\omega_0} = \frac{1}{2\pi\sqrt{R_2 C_1}} \qquad (1)$$

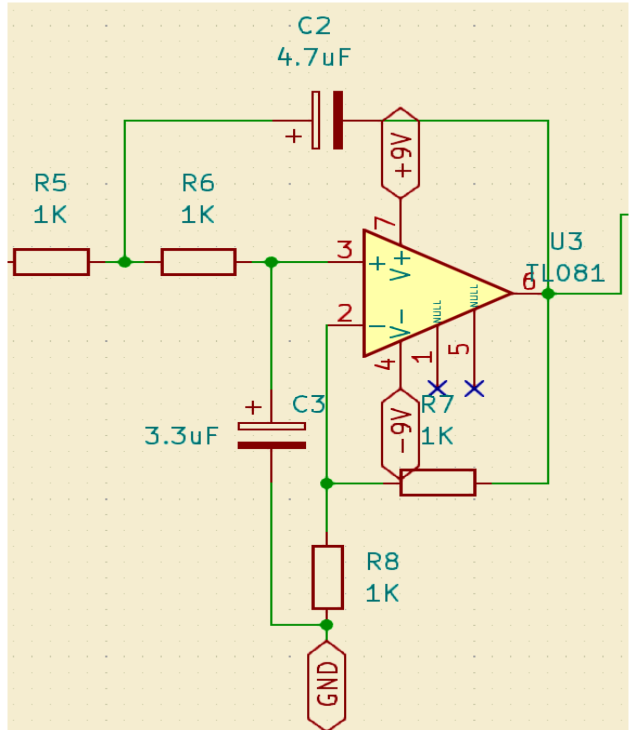

Fig. 4 Low-pass filter design

To obtain the desired gain (A_0) of the high-pass filter, Equation 2 was used, where R_3 and R_4 are equal to 1kΩ.

$$A_0 = 1 + \frac{R_3}{R_4} = 1 + \frac{1k\Omega}{1k\Omega} = 2 \qquad (2)$$

Low-Pass Filter

A second-order Sallen-Key filter was used with a cutoff frequency of 40Hz in order to eliminate high-frequency noise and interference that might be present. In Figure 4, the base circuit for this filter is shown.

To obtain the desired cutoff frequency of approximately 40Hz, Equation 3 was used. The values of the resistors R_5 and R_6 are equal to 1kΩ, and the values of the capacitors C_2 and C_3 are 4.7μF and 3.3μF, respectively.

$$f_c = \frac{1}{2\pi\omega_0} = \frac{1}{2\pi\sqrt{R_5 R_6 C_2 C_3}} \qquad (3)$$

To obtain gain (A_0) of the low-pass filter, Equation 4 is used, where R_7 and R_8 are equal to 1kΩ.

$$A_0 = 1 + \frac{R_7}{R_8} = 1 + \frac{1k\Omega}{1k\Omega} = 2 \qquad (4)$$

Postamplification and Offset

Here, the purpose is to scale and regulate the signal in a range of 0 to 5V (Figure 5) to allow digital reading and processing with the microprocessor in the directional control stage.

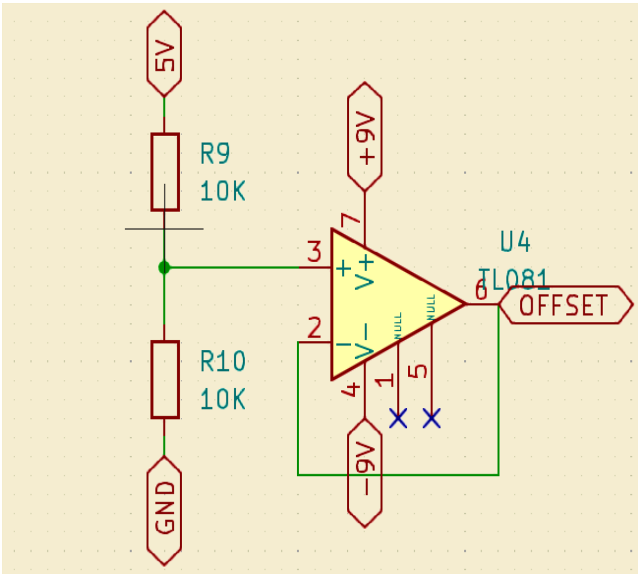

Fig. 5 Offset set-up

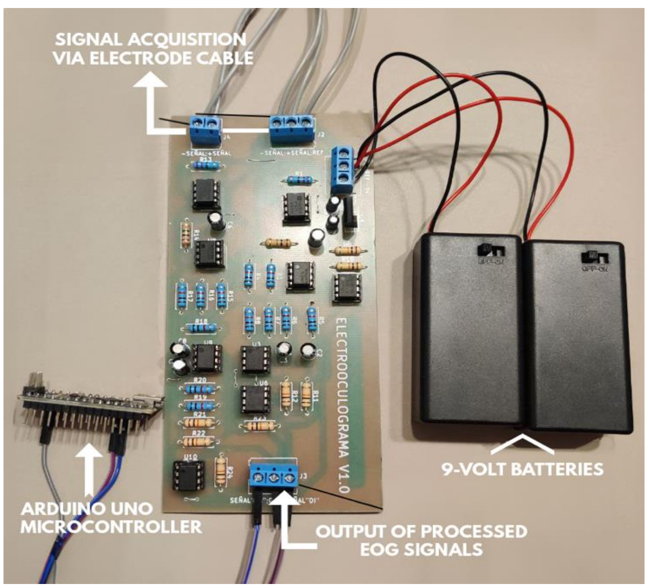

Fig. 6 PCB of the signal processing stage

The printed circuit board (PCB) of the signal processing stage is shown in Figure 6. A 9-volt battery is needed for this PCB.

2.3. Directional Control Design

The control and steering system used software and hardware based on Arduino, as it is a friendly and accessible platform for integrating input signals, actuators, and other electronic components. The Arduino Nano was used to store the control algorithm and receive the signals from the preprocessing stage. The L298N power module was used to direct the output voltage to the DC motors. As can be seen in Figure 7, the L298N module is powered by a 12V battery DC. The steering control system's algorithm is based on the preprocessing of the signals coming from the previous stage,

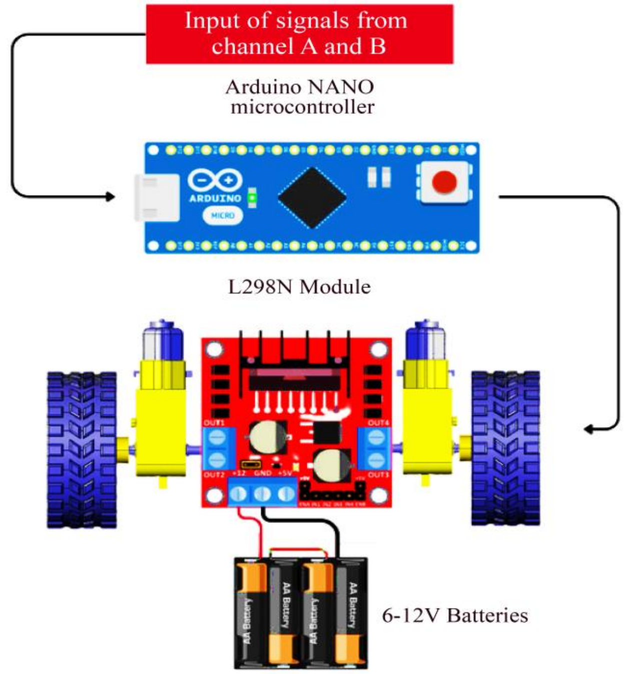

Fig. 7 Steering control system

which are read and stored in variables and then classified into certain ranges generated as products of some type of eye movements. As seen in Figure 8, conditional logic is generated to evaluate these values and indicate the motor drive module in which direction the user wishes to move the wheelchair.

3. Results and Discussion

The present study proposed a low-cost system to control a wheelchair using eye movements through the analysis and processing of EOG signals. The results obtained and presented in this section demonstrate the feasibility of using this type of signal to allow a person with quadriplegia to move with a certain degree of autonomy using a wheelchair, thus accurately classifying the different eye movements (looking up, down, right, and left).

The tests of our steering control system were carried out in a laboratory environment to verify first the quality of the signals acquired through the filtering applied in the preprocessing stage. To this end, the electrodes were positioned on the test user's face, and the signal conductor cables were connected to the PCB inputs that performed the signal preprocessing.

With the help of a multimeter and an oscilloscope, it was evaluated whether the resulting signal was clear and sensitive enough to capture any eye movements. The results demonstrated precision in amplifying and partially eliminating signal noise, thereby obtaining EOG patterns suitable for subsequent processing (as seen in Figures 9 and 10). Additionally, the system's response time was less than 1 second on a set of 10 direction commands.

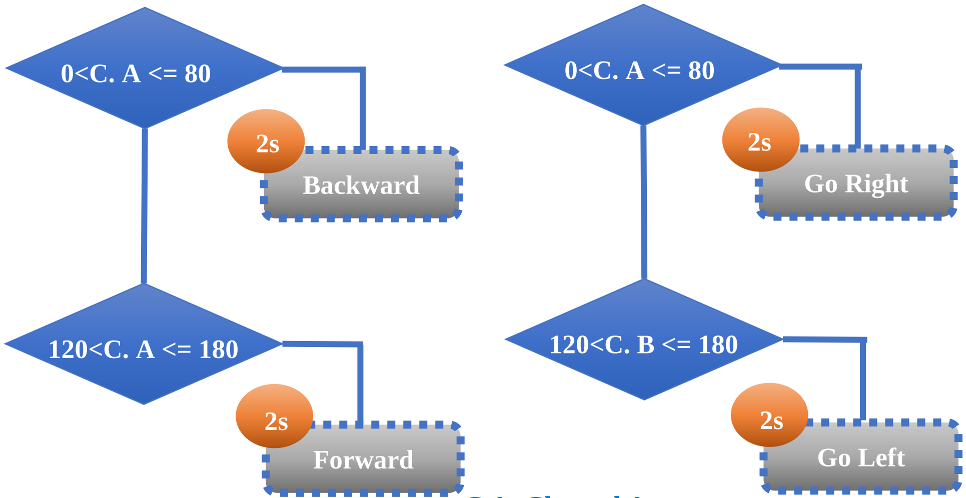

Fig. 8 Block diagram of the steering control logic

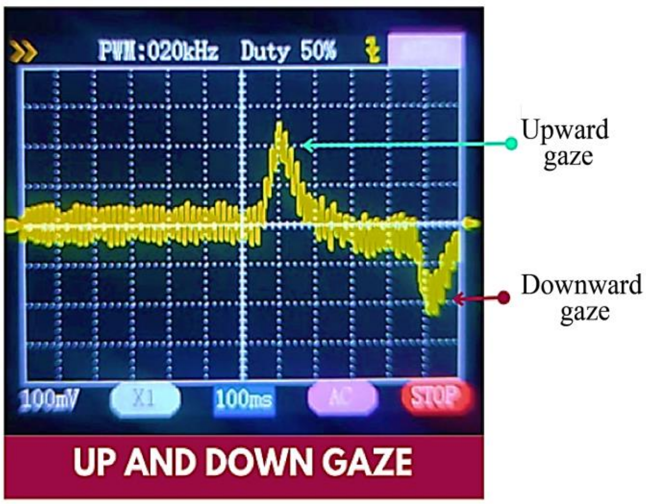

Fig. 9 EOG signals from upward and downward gaze measured with the oscilloscope

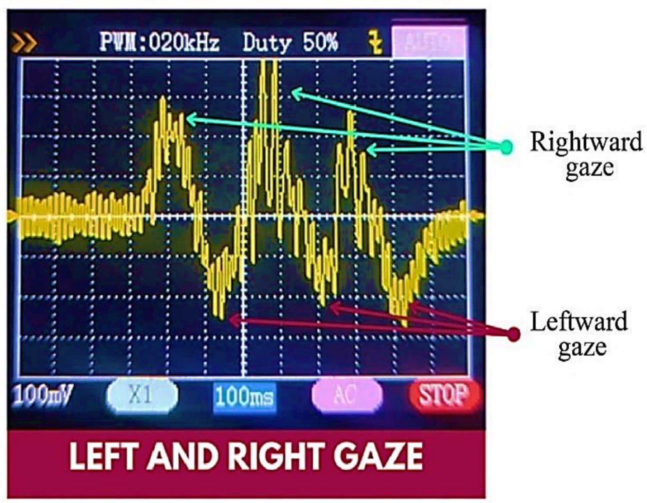

Fig. 10 EOG signals from right and left gaze measured with the oscilloscope

Table 1. EOG signal response time tests

Tests	Up	Down	Right	Left
Test 1	High	High	High	High
Test 2	High	High	High	High
Test 3	High	Middle	High	Low
Test 4	High	High	High	Low
Test 5	Middle	High	High	Low
Test 6	High	High	Low	High
Test 7	High	High	High	High
Test 8	High	High	Low	High
Test 9	High	Middle	High	High
Test 10	High	Low	Low	High
Effectivity	95%	80%	80%	70%

As seen in Table 1, the system has an average effectiveness of 81% with respect to the system response time to identify a signal of quality and quick response. This could be verified on the oscilloscope by measuring channels A (for up and down eye movements) and B (left and right eye movements) once they pass through the PCB that performs the signal preprocessing. To measure the effectiveness, ranges were established based on the characteristics of the wave: “High” is when the response time is less than one second. The signal voltage is greater than 1.5V and less than 0.8V, “Middle” for a time response less than 1, but with a voltage value between 0.8V and 1.5V, while “Low” only differs from Middle because the delay is greater than 1 second and is considered a failed test. This precision varies according to the user since the area of greatest sensitivity around the eye must be identified to position the electrodes accordingly.

Table 2. Tests of forward movement

Tests	Channel A reading	Result
Test 1	380	True
Test 2	430	True
Test 3	358	True
Test 4	362	True
Test 5	395	True
Test 6	402	True
Test 7	388	True
Test 8	376	True
Test 9	392	True
Test 10	409	True
Test 11	404	True
Test 12	391	True
Test 13	361	True
Test 14	445	True
Test 15	398	True

Table 3. Tests of backward movement

Tests	Channel A reading	Result
Test 1	42	True
Test 2	10	True
Test 3	49	True
Test 4	32	True
Test 5	45	True
Test 6	42	True
Test 7	36	True
Test 8	39	True
Test 9	33	True
Test 10	41	True
Test 11	8	True
Test 12	38	True
Test 13	22	True
Test 14	68	False
Test 15	15	True

The steering tests were based on evaluating the ability of the developed system to respond to the travel direction desired by the user. They were executed in a laboratory to ensure strict compliance with security measures and isolate surrounding signals around the system. To do this, all electronic or electrical equipment was disconnected from the home network. The system was operated with direct power from direct current batteries to reduce the risk of possible leaks of unwanted signals. A display screen for reading channels A and B was used to ensure proper data collection, corresponding to the signals processed by the system and generated by the 4 eye movements (looking up, down, right, and left). In addition, there was a small prototype electric vehicle, which was responsible for executing the action required by the user by sending signals to the L298 power module to steer the motors (of 180 rpm each) in a desired direction.

To test the steering control system, a total of 60 tests focused on measuring the real effectiveness of the system in the laboratory were carried out. First, 15 tests in the forward direction were performed. Here, it was verified that the system correctly recognized and responded to the eye movements that indicated the intention to go forward. The tests were carried out by connecting the user to the Zoll ECG electrodes in the areas surrounding the eye. The signal outputs scaled to 5 V DC (A and B channels) were connected to the Arduino microcontroller to be read in analog format (0 to 1024).

After processing by part of the control algorithm, the small vehicle with two wheels that simulate the wheelchair moved forward. This was made possible by the two motors connected to the L298N power module. The results showed a high precision in the classification of the forward movement, with a success rate of 100% of the 15 tests performed (as seen in Table 2), which consisted of looking up repeatedly, then capturing the value of channel A that should always be greater than 350.

Second, 15 backwards-direction tests were carried out. Similarly, as in the forward movement tests, the system's ability to detect and respond to the eye movement directing the vehicle in a backward direction was evaluated. On this occasion, the dynamic that the user followed was to look down repeatedly. After carrying out the tests, promising results were obtained with an accuracy of 93%; 14 tests out of 15 successfully performed this movement (as seen in Table 3), indicating thus a reliable response. Third, the next 15 tests were to validate rightward steering. This test examined whether the system could properly recognize and respond to the repetitive movement of looking to the right. The results achieved showed an accuracy of 87% in the proper direction of this movement since of the 15 tests developed, 13 were successful.

Table 4 shows that out of 15 tests, 2 were executed with positive results. To do this, it was necessary to configure an input pin of the Arduino Nano to receive the data from channel B; afterwards, the control algorithm was executed, and within this, a detection range of the intention to move to the right was defined. When the value of channel B is greater than 350, a test is successful.

Table 4. Tests of rightward movement

Tests	Channel B reading	Result
Test 1	410	True
Test 2	430	True
Test 3	368	True
Test 4	367	True
Test 5	375	True
Test 6	320	False
Test 7	368	True
Test 8	396	True
Test 9	381	True
Test 10	418	True
Test 11	395	True
Test 12	384	True
Test 13	376	True
Test 14	345	False
Test 15	371	True

Table 5. Tests of leftward movement

Tests	Channel B reading	Result
Test 1	12	True
Test 2	31	True
Test 3	89	False
Test 4	33	True
Test 5	15	True
Test 6	36	True
Test 7	18	True
Test 8	22	True
Test 9	29	True
Test 10	72	False
Test 11	38	True
Test 12	47	True
Test 13	8	True
Test 14	12	True
Test 15	49	True

Table 6. Effectivity rates in the test performed

Tests	Up	Down	Right	Left
Successful	15	14	13	13
Failure	-	1	2	2
Effectivity	100%	93%	87%	87%

Once again, it was demonstrated that the system has a significant capacity to detect and respond to eye movements swiftly. Finally, we validated the leftward steering with the last 15 tests. As in the previous tests, the user fixed his gaze repeatedly in the left direction, which sent signals through the electrodes first to the Arduino and lastly to the two motors. The results revealed an accuracy of 87% as 2 tests failed due to the signal being outside the set range (as seen in Table 5).

Table 6 shows a summary of the tests in the four directions. Overall, an effectivity rate of 92% was achieved for our control steering system.

The results obtained in this study are consistent with those reported in other studies [9,10,11,12,13], where the effectivity rates obtained in the four steering tests (looking up, down, right, and left) of this work are comparable to those found in the aforementioned studies. The approach based on EOG signals and the use of an Arduino controller, together with the architecture that simulates the wheelchair, has proven to be effective in the detection and precise response to eye movements, allowing intuitive and reliable control of a wheelchair's direction.

On the one hand, the tests developed to verify the presence and quality of the signals acquired through the filtering and preprocessing stages proved to have an average effectiveness of 81% with the system proposed in the present investigation, which is comparable with the other studies [14, 15, 16] findings. For instance, [14] obtained outstanding results of 93% in the effectiveness of preprocessing in obtaining high-quality signals for wheelchair control. On the other hand, the direction tests carried out in the present investigation have shown an assertiveness of 92% in identifying the user's eye movements to direct the wheelchair from one place to another.

Finally, the results found in regard to the overall steering control are consistent with those reported in [5, 6, 9], which also achieved a high effectivity of approximately 95% in eye movement detection and steering of a wheelchair using EOG signal preprocessing.

However, the aforementioned works used different methods to determine the user's eye movements, for example, using a visual element to guide the traceability that the human eye must have or working commands based on blinks.

4. Conclusion

The low-cost steering control system based on EOG signals and an Arduino nano has proven to be a reliable and accessible solution to allow people with mobility disabilities to control their wheelchairs intuitively and efficiently. The results obtained support the relevance and effectiveness of the proposed design.

In the filtering stage, EOG signal preprocessing was implemented to obtain a quality signal, which was essential for the system's accuracy. Effective noise elimination and obtaining a reliable signal proved crucial for the correct control system operation. The tests that were executed proved the ability of the steering control system to adequately identify and respond to the user's desired intention of movement.

Our results, thus, suggest a promising path for future research and development in the field of mobility assistance. This work represents an important advance in the application of assistive technology. It opens new possibilities to improve the quality of life of people with motor disabilities through innovative and adaptive control interfaces.

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