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Teleoperation Training Environment for New Users of Electric Powered Wheelchairs Based on Multiple Driving Methods

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ABSTRACT Currently, diverse existing training environments help new users of electric powered wheelchairs (EPWs) learn how to drive, acquaint, and improve their abilities with these assistive devices. Several authors are developing such environments, and most of them use virtually simulated wheelchairs. Despite the similarities between virtual and real wheelchairs, it is easier to drive the real device, because representation of the wheelchair physical behavior is still a problem for virtual simulated environments. Concerning the driving methods, most of them are based on a joystick, which does not give the opportunity for users to test, practice, and acquaint themselves with new technology, such as driving through eye movements. This paper implements and tests a more realistic approach to a training environment dedicated to new users of EPW. The proposed system is based on a real EPW controlled by teleoperation, and it is flexible enough to attend to multiple driving methods. An architecture that allows a user to send command messages to control a real EPW through the Internet was implemented to test the system. The implemented driving methods used were conventional joystick, eye-tracker, and a generic human–machine interface. The experimental results suggest that new users can practice safely using a real EPW through the Internet, even in a situation with a communication delay of 130.2 ms (average). Furthermore, the proposed system have shown itself to be a potential tool for attending to new EPW users with different types of disabilities and to be a low-cost approach that could be applied in developing countries.

INDEX TERMS Electric powered wheelchair, eye-tracker, HMI, joystick, teleoperation, training environment.

I. INTRODUCTION

The demographic census of Brazil from the year 2010, pointed out that 13.2 million people have a motor disability, which is approximately 7% of the population [1]. For people with motor disabilities, the electric powered wheelchair (EPW) plays a major role in enhancing life quality and well-being. The EPW is an assistive technology device that helps people with disabilities to move easier compared to a manual wheelchair. Users can conduct the device by a joystick, choosing direction and speed. The regular device has a battery system, electric motors, and an electronic circuit for actuation. This device allows users to move freely, helping them participate in activities such as education, work, and social entertainment and to have better access to hospitals and clinics [2]. Every year ordinary people suffer accidents or diseases that cause disabilities, making them new users of EPW. Additionally, this device is essential to help people with severe disabilities (cerebral palsy, multiple sclerosis, myopathy, and others) [3].

The training for new wheelchair users benefits people who are not acquainted with this device. This training aids in the development of skills to reduce the accident risks,

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especially in public places such as streets, schools, hospitals, malls, supermarkets, etc. However, when the training is performed in a real wheelchair, it may cause physical and material damage [2]. In this context, virtual wheelchair training environments have helped users become familiar with this assistive technology. These environments aim to avoid course accidents during driving practice. However, the evolution of those environments is still a very difficult task in relation to the physical representation of wheelchair behavior [4], [5]. Another observed difficulty is creating an immersive experience [6]. In addition to this characteristic, another aspect that should be improved in the current training environments is the inclusion of different methods to control the EPW. For instance, the studied training environments [4], [5], [7]–[9] do not cover the eye-movement driving method, which has a major role in allowing people with severe disabilities to operate the device. This method and others, such as driving through muscle movements or brain signals, may help people who cannot drive with a conventional joystick.

Studies show that independent mobility increases vocational and educational opportunities, reduces dependence on caregivers and family members, and promotes self-reliance [10]. Consequently, facilitating independent mobility tends to improve the quality of life for people with motor disabilities. Therefore, training environments with multiple input options become significant for new EPW users, since they allow the first contact with these new technologies.

Hence, this study focusses in two different aspects. The first is to overcome the problem of representing the physical behavior of the wheelchair, using a low-cost training environment that can be applied in developing countries, such as Brazil. The second is to solve the problem of the limited number of driving methods for wheelchair training systems.

Therefore, to reach these goals, this work proposes, implements, and tests a novel training environment for new users of EPW. This approach is based on teleoperation over the Internet, combined with multiple driving methods. Different scenarios were created to test each driving method and to investigate the delay impact in long-distance teleoperation. The applied techniques, methods, materials, and results will be presented, and further, the benefits of using teleoperation of a real EPW for practice will be discussed.

Furthermore, this paper is organized as follows. Section II describes the current state of the art of virtual wheelchair simulators, and teleoperation systems based on the Internet. Section III presents the development of this proposal, which first introduces the concept of the wheelchair teleoperation system, and then presents the input methods, electrical signals, and hardware, followed by the communication requirements and the evaluation methods. Section IV describes the scenarios for the experiments and the results. Section V presents a discussion of the experimental results and contrast with related works. Finally, Section VI addresses concluding remarks and future work.

II. RELATED WORK

The related work is divided into three parts. First, it describes several approaches regarding the virtual wheelchair training simulators. Second, it presents the state of the art of teleoperation systems based on the Internet. Third, it addresses the selected tools and techniques to perform the teleoperation in this project.

A. VIRTUAL TRAINING ENVIRONMENTS FOR WHEELCHAIR USERS

In recent years, several approaches for virtual simulators have been developed for wheelchair users to practice driving. Some authors compared real and simulated wheelchairs. Others created virtual environments more similar to the real world, adding people and objects. Further, authors proposed systems to reach a specific group of people, such as children with disabilities.

Archambault *et al.* [5] developed a wheelchair driving simulator and conducted a study to compare driving real and virtual wheelchairs. They showed that, on average, half of the tasks performed in the virtual environment seemed to be more difficult. This outcome occurred because the participants increased the average number of joystick commands and the time to complete the course. These results supported the conclusion that it is difficult for virtual environments to be realistic for real-world representation.

John *et al.* [4] compared their simulated wheelchair training environment to the real world. They noted that despite subtle differences, users performed more maneuvers in the virtual environment compared to the real world. Another difference was that more time was required to finish the course and that more collisions occurred in the virtual environment. These results provided another example of the difficulty of creating a training environment that closely resembles reality.

Morère *et al.* [7] created a simulator for training electrically powered wheelchair drivers. Their work presented a virtual simulation with people and objects in the scene intending to create a more realistic situation. However, the authors claimed that some characteristics related to the speed of the wheelchair and objects in the scenario should be improved.

Rodriguez [8] developed a virtual wheelchair training environment for children. The visual aspects of the simulation were adapted to catch their attention and interest. Her work showed a great potential to reach specific types of people, such as children with disabilities.

Rossol *et al.* [9] designed a framework for virtual wheelchair training. A software system was created with the possibility to customize the driving scenario to add obstacles such as chairs, cones, and tables. They also presented a method to automatically allocate the objects according to user driving skills. However, similar to [4], [5], and [7]–[9], those authors only used the joystick as a driving method.

B. TELEOPERATION SYSTEMS BASED ON THE INTERNET

This part presents the current state of the art of teleoperation systems based on the Internet. The purpose is to find the most appropriate tools for EPW teleoperation. For that, some authors used different communication architecture and network infrastructure, such as cellular networks (3G/ 4G) and wired broadband Internet. Further, the current video streaming tools, network protocols, and metrics to evaluate communication are presented.

Xu and his co-authors developed a teleoperation system for a humanoid robot. In their work, they used the Internet through a 3G network for communication between the operator (master) and robot (slave). To provide the master real-time feedback from the slave site, the authors applied video streaming. Therefore, to reduce the throughput of data exchange, they applied codec h.264. The tool for the codec and video streaming was ffmpeg, which is an open source library. The network protocols were Real-time Transport Protocol (RTP) and User Datagram Protocol (UDP) [11].

Ha *et al.* [12] developed an architecture to control wheelchairs at a distance focused on outdoor environments. The messages for the master-slave communication scheme were sent through the Internet by a 4G network. The video streaming was through Skype. To evaluate the communication the authors measured the round-trip time (RTT) and the cellular network signal intensity. The software to perform this evaluation was Wireshark. The network protocols were Transmission Control Protocol (TCP) and UDP. The authors used a desktop computer on the slave site.

Gonzalez *et al.* [13] designed a telepresence system for a remote-controlled helicopter. The system uses two smartphones where the first streams the video in real-time using Skype, and the second takes pictures of the target according to the operator's commands. For communication, a 3G cellular infrastructure was applied.

Manzi *et al.* [14] presented a generic cloud teleoperation system for a mobile robot. The Azure Cloud Platform was used, and a web-based interface was applied to mobile devices (smartphones and tablets), the protocol was Hypertext Transfer Protocol (HTTP). Internet access was through a 4G network.

Shenai *et al.* [15] designed a model for real-time telesurgical collaboration. Their work allows remote participants to have the same vision the doctor has during surgery. Therefore, those participants can help the doctor through medical opinions, video and augmented reality interaction. It used a wired Internet connection and a commercial teleconference device.

Kato *et al.* [16] created teleoperation for pneumatic systems. They used a 4 degrees of freedom (DOF) robotic arm and a gripper to take objects. Skype was used for video transmission and UDP was used for commands, and they used a wired Internet connection. The distance between sites was 30 km.

C. ADDRESSED APPROACH

This work intends to provide a more realistic approach after considering the current state of the art of wheelchair training environments. In this proposal, the user will remotely control a real wheelchair, being completely safe while driving it. During this teleoperation, the user will perform remote tasks without being physically present where the operation is taking place. Further, to reach people with different levels of disabilities, this work will offer different driving methods for user training. Moreover, our system will be open source and offer the flexibility to include more driving methods for user training.

TABLE 1. Selected methods and tools to implement the teleoperation training system for new EPW users.

Selected methods and tools	
Internet communication infrastructure	Wired broadband Internet
Video streaming and codec	ffmpeg
Network Protocols	UDP/HTTP
Metric to evaluate the communication	RTT
Network traffic analysis	Wireshark
Hardware (computer role) on the slave site	Embedded system

Regarding the state of art of teleoperation, it is possible to control in real time a robotic platform through the Internet. Some works rely on cellular infrastructure, 3G, and 4G. However, due to signal dependency, it might not be the best option for indoor places, such as hospitals. A more appropriate method for indoor places is a wired Internet connection, which was applied by some authors [14], [15]. Although for short distance communication, it will be necessary to add extra wireless connection devices.

Many authors applied codecs to reduce the throughput when considering the video streaming feedback from the slave to the master. In this project, this method was chosen. Also, to accomplish this goal, the library ffmpeg will be used to perform the video streaming and codec since it is an open source tool.

The authors used different network protocols, such as UDP, TCP, RTP, and HTTP. This work is going to apply UDP for the commands because it does not require message confirmation and provides a faster response. For video streaming, HTTP was chosen, since it facilitates the synchronization of request/response between the server/client.

To evaluate the communication, some authors applied the RTT as a parameter and, moreover, the software Wireshark for network analysis. This work uses both methods.

Generally, the authors applied a smartphone or desktop computer on the slave site to receive data from the master. Since one of the objectives of this project is to develop a low-cost system that can be easily applied in developing countries, this work will use a low-cost embedded system on the slave site to perform this role. Table 1 presents the selected methods and tools for the EPW teleoperation.

III. DEVELOPMENT OF THE TRAINING ENVIRONMENT

The development is divided into two parts. The first is the training center (TC), where the user is going to be located. Users will choose one driving method to control the

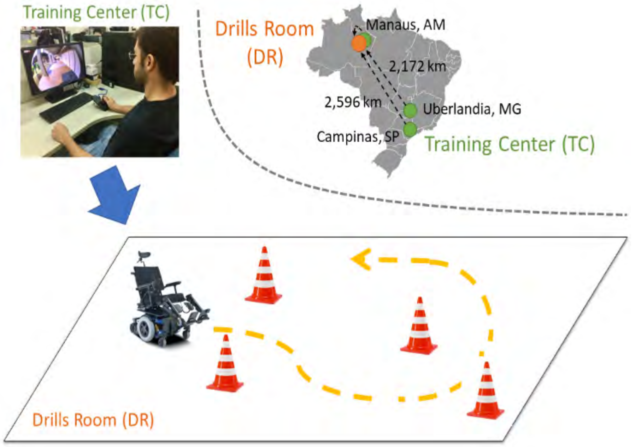


FIGURE 1. **Conceptual diagram of the teleoperation training system.**

EPW remotely, and they will have a computer screen to receive real-time video feedback. The second part is the drills room (DR), where the EPW will be located, the remote commands are received and executed, and where the video is recorded and transmitted in real time.

The TCs are initially located in Brazil in the cities of Campinas and Uberlândia. Moreover, the DR is located in Manaus, Brazil. Figure 1 presents the conceptual diagram of the training system, containing the distance between the cities where the DR and TCs are located. Therefore, with only one DR, it will be possible to practice wheelchair driving from different TCs. The idea is to install TCs inside hospitals, clinics and physical rehabilitation centers in different cities in Brazil.

During system operation, the user's remote commands are translated to electric signals that move the wheelchair. Meanwhile, cameras provide the user with different points of view of the wheelchair environment. Figure 2 shows a general view of how the system operates.

A. TRAINING CENTER

The training center consists of a place where new users go to learn how to drive the EPW and improve their skills. Users can choose different driving methods (a.k.a. control interfaces). Those are chosen according to user movement limitations. In our system, there are three types of control interfaces: joystick, eye tracker, and generic human-machine interface (GHMI). The TC can be easily set up for the patient (new user) to start practicing. It requires a computer connected to a gateway with wired broadband Internet, and one of the control interfaces connected to the computer.

1) JOYSTICK CONTROL INTERFACE

The first driving method to be presented uses one joystick. That is the conventional way of driving a wheelchair. Laboratory tests were performed to verify the voltage levels generated by the original joystick of the EPW model Freedom Carbon. It was observed that the input reference consists

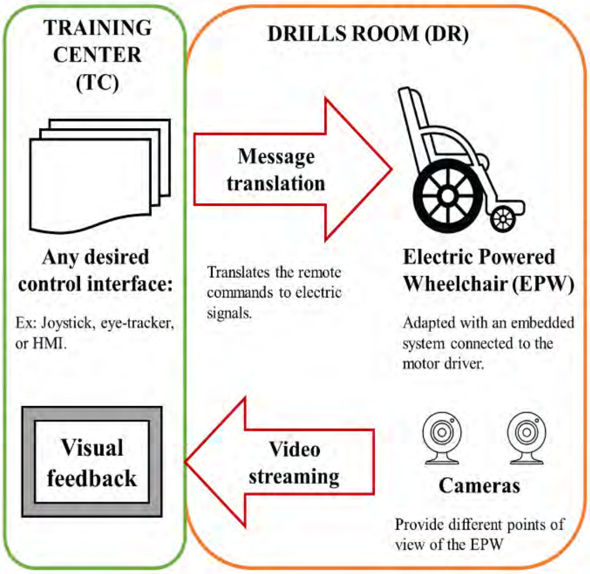


FIGURE 2. **General view of how the system operates.**

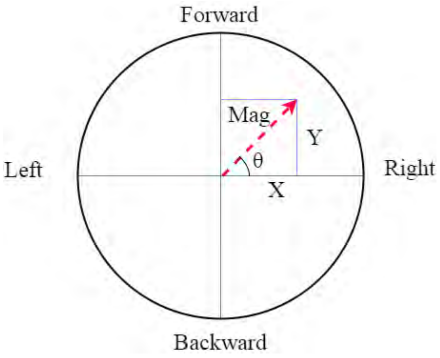


FIGURE 3. **Mathematical representation of joystick behavior.**

of a vector of magnitude and angle generated by the joystick movement. The magnitude corresponds to the speed, and the angle corresponds to the direction. Mathematically, in a simplified way, the behavior is interpreted according to equations 1, 2 and Figure 3.

$$Mag = \sqrt{X^2 + Y^2} \tag{1}$$

$$\theta = \tan^{-1}\left(\frac{Y}{X}\right) \tag{2}$$

Where:

- Mag: Magnitude (speed).
- θ : Angle (direction), measured from the positive X axis to the point of interest.

The implementation of this control interface consists of the original EPW joystick connected to an embedded system (Arduino Uno), as presented in Figure 4. This embedded system reads the voltage analog signals using two ADCs (analog-to-digital converter) with 8-bit resolution. One for the X and the other for the Y signals. The messages are sent from the Arduino Uno to the computer through USB with

FIGURE 4. **Original EPW joystick adapted to teleoperate by distance.**

a baud rate of 9600 bps. Each command is transmitted at a frequency of 13.33 Hz.

2) EYE-TRACKER CONTROL INTERFACE

This control interface was designed to attend to people with severe disabilities such as those who cannot drive the wheelchair by the conventional method (joystick). With the eye-tracker control interface, users can drive using eye movements. Therefore, to create this interface the Tobii 4c device is being used, which is a commercial eye-tracker that has an API to facilitate software development. In this driving method, the user focuses on one arrow referring to the desired command (forward, backward, left, right and stop).

During the teleoperation, the eye gaze position of the user on the computer screen is captured. Moreover, to avoid unintended commands, they are only generated when the user gazes at of the one arrows for at least 500 milliseconds. A map of pixels was constructed with a specific range of position for each command. This map is an image with the same resolution as the computer screen (1920 x 1080). Figure 5 shows this interface and the values referring to the pixel positions of rows (X) and columns (Y). Every time a command is generated, the computer plays a sound for confirmation. For instance, if the user gazes at the forward arrow, the computer plays the sound "forward." Moreover, the same happens for the other commands. Furthermore, the positions of the arrows are based on Ktena's screen-based eye tracking technique that presented a better performance than other eye-tracking techniques [17].

3) GENERIC HUMAN-MACHINE INTERFACE

The generic human-machine interface (GHMI) consists of a graphical user interface (GUI) with discrete commands representing the movements of the wheelchair. The user drives by clicking on the buttons corresponding to the desired direction. When it occurs, the EPW moves continuously, and the user can stop by clicking on the square button (in the middle of the arrows). Figure 6 presents this interface.

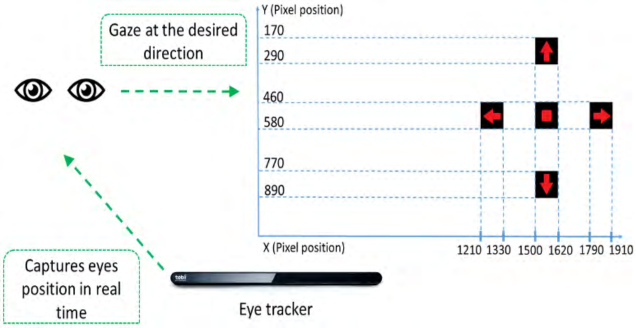


FIGURE 5. **Eye tracking interface with the pixel position ranges to generate EPW commands.**

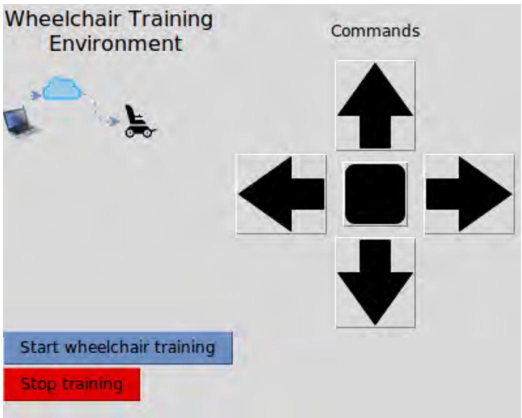


FIGURE 6. **Generic Human Machine Interface (GHMI) that can be easily adapted to new driving methods.**

That is one of the most important control interfaces of this project because it has the framework to include other driving methods. Future developers wanting to use this open source project can easily include other input methods. For example, if including muscle signals as a driving method is desired, it is possible to include it by reusing the GHMI. The developer will not have to worry about all the complexity of creating the communication between the master-slave, converting the command messages to electrical signals to move the EPW, establishing a video streaming for the feedback, and other aspects. The requirement is to simply import our software as the main structure of the code and follow our command pattern, which is presented in Table 2.

B. DRILLS ROOM

This part presents the DR, which is the place where the EPW will be located. The user accesses the DR through the Internet to send commands and receive video feedback from the wheelchair. In this place, the user needs to accomplish pre-defined tasks during practice. Therefore, each component of the DR is going to be presented.

1) USER-WHEELCHAIR BOARD

This user-wheelchair board has the role of generating analog voltage levels to command the EPW. There is an

TABLE 2. Examples of commands messages, and analog voltage sent to the EPW driver.

Command	Polar Coordinate		Generated Voltage (V)		Wheelchair Movement
	θ	*Mag.*	*X*	*Y*	
X=0%,Y=100%	90°	100	2.5	3.5	Forward
X=0%,Y= -100%	-90°	100	2.5	1.5	Backward
X=100%,Y=0%	0°	100	3.5	2.5	Right
X= -100%,Y=0%	180°	100	1.5	2.5	Left
X=0%,Y=0%	0°	0	2.5	2.5	Stop

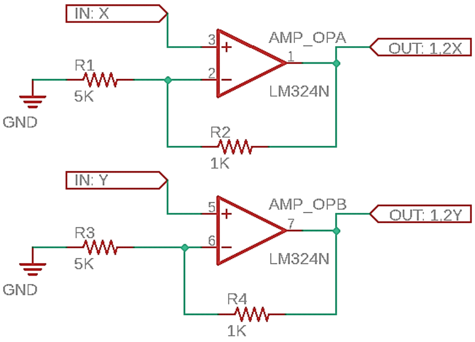


FIGURE 7. Signal conditioning circuit for the user-wheelchair board.

embedded system with two Digital-to-Analog Converters (DACs) to accomplish these features, one for the X-axis, and the other for Y. Those values apply the same concept presented in Figure 3. Each DAC has a resolution of 8 bits. Further, to send the message using the network, it was necessary to create a command pattern that contains both values of X and Y in a single message. Those values vary from −100% to 100% for each axis. Table 2 presents some message examples.

The embedded system used in the EPW is the UDOO-dual board. This board comes with an ARM processor, a WiFi network adapter, and an integrated Arduino DUE (used for the DACs). The ARM processor communicates with the Arduino DUE through the serial protocol. Moreover, it was necessary to apply a signal conditioner to amplify the voltage level. That occurred because the maximum voltage level generated by the DAC is 3.3 V, but the necessary level for the wheelchair driver is 3.5 V. Equation 3 shows the amplifier gain calculation. Further, the designed signal conditioner is the electronic circuit with non-inverting operational amplifiers presented in Figure 7. The fine voltage adjustment is performed via software. Figure 8 presents the hardware components used to adapt the EPW for the teleoperation.

$$Av_{non-inverting} = 1 + \frac{R2}{R1} = 1 + \frac{1K}{5K} = 1.2 \tag{3}$$

2) VIDEO STREAMING

Video streaming provides the user real-time video feedback from the DR. There are two different cameras doing that. The first gives a first-person view (FPV), simulating the vision of a person seated in the wheelchair. The second provides a third-person view (TPV), giving awareness of the training environment. The required steps for transmitting and receiving video are presented in Figure 9.

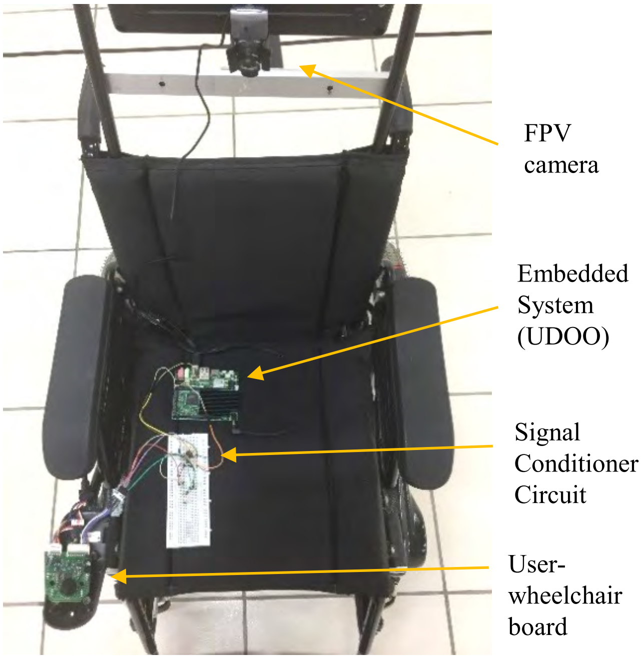


FIGURE 8. Hardware components to adapt the EPW for teleoperation.

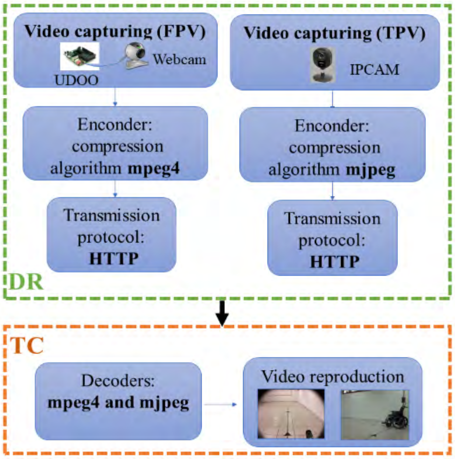


FIGURE 9. Video streaming transmission and reproduction process.

The resolutions of the FPV and TPV cameras are 800x600 and 320x240, respectively. The frame rate for both cameras is 20 fps. The eye-fish lens was attached to the FPV camera to provide a wider view. There is no buffer for the client side or the server that results in a faster response to video streaming. The ffmpeg library for creating the video streaming of the FPV camera was used. Compiling this tool into the embedded system was necessary. On the client side, the portable media player (ffplay) is used to reproduce video. In addition, both tools, ffmpeg and ffplay, are open-software.

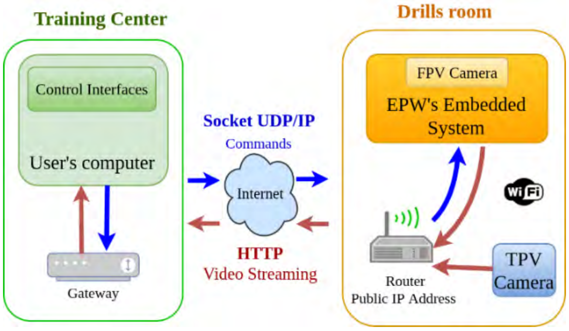


FIGURE 10. Communication architecture and data flow for the teleoperation.

C. COMMUNICATION ARCHITECTURE

The communication between the TC and DR is performed through the Internet. The exchange of command messages is based on socket UDP. This protocol has a low delay since it does not require confirmation on the receiver side. The socket client is located at the TC, and the socket server at the DR. The messages are string type and have an average throughput of 22 kbit/s. The video streaming protocol is HTTP, with an average throughput of 865 kbit/s for the two cameras together. The total throughput for the data is 887 kbit/s. Moreover, the network traffic was analyzed through the Wireshark software. Figure 10 presents the system communication architecture and data flow. Figure 11 shows a full view of the hardware components.

Furthermore, while the training is occurring, the quality of the communication between the TC and DR is evaluated. The parameter to measure that is the RTT, which consists of round-trip time delay. On every second of the training, this parameter is measured and saved into a log file. Then, the results are statistically analyzed to calculate the average, standard deviation, maximum and minimum RTT values through MATLAB. It is important to mention that this communication evaluation was performed to test the system. Although, for future use, it will not be necessary.

D. EVALUATION OF THE TRAINING PERFORMANCE

To determine the training system performance, two variables of interest are measured. The first is total time spent to finish the course. The second is the number of generated commands. Therefore, to determine the number of commands, the X and Y data from the user command messages are recorded into a log file. For that, an algorithm was created in MATLAB. The objective is to automatically detect how many commands were generated. Equations 4 and 5 present the first calculation procedures. The variable λ represents the sum of absolute values of X and Y. Then, the result is normalized and becomes $\hat{\lambda}$.

$$\lambda = |X| + |Y| \tag{4}$$

$$\hat{\lambda} = \frac{\lambda}{max(\lambda)} \tag{5}$$

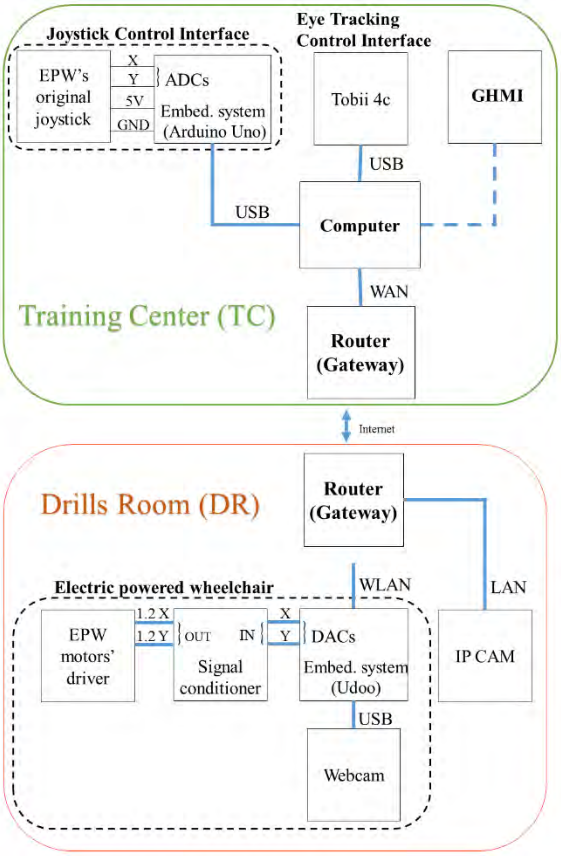


FIGURE 11. Full view of the hardware components of the teleoperation training system.

Next, the threshold function is applied at $\hat{\lambda}$. The appropriate value for the threshold was chosen after several tests. It was observed that the lower the value is, the greater the sensitivity in detecting commands. An example of collected command data from the joystick is shown in Figure 12. The graphic shows X and Y amplitude versus the sample number. The application of the command detection algorithm is presented in Figure 13. The number of commands is counted automatically using the MATLAB number of regions function.

The purpose of command counting is to compare user performance throughout all the training sessions. For instance, for the first time performing a route, a user needed 30 commands to complete, but after practicing, the number of commands was reduced to 21. This example showed an improvement of 30% in performance over the initial values. The command counting algorithm can also help determine which control interface is more appropriate for the new user to drive the EPW. The user could test different control interfaces and choose the most effective (least number of commands).

IV. EXPERIMENTAL RESULTS

This section presents the experimental results based on the methods proposed in previous sections. The participating researchers led the experiments (n=3), and there was no concern to create a control group, because that was not the

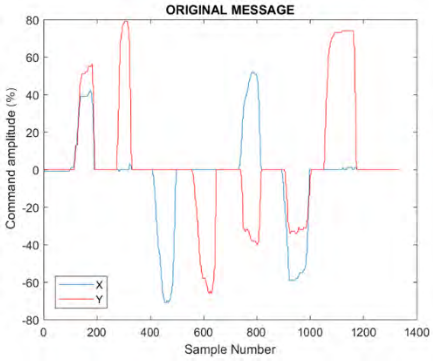


FIGURE 12. **Data example of a message generated with the joystick.**

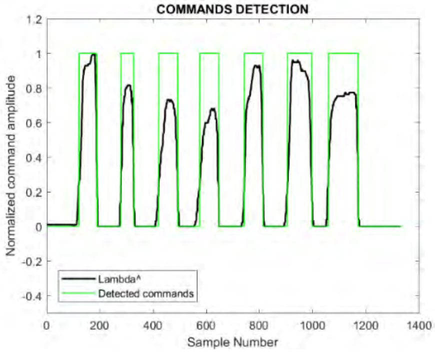


FIGURE 13. **Graphic representation of the command detection algorithm.**

TABLE 3. **Scenarios to evaluate the teleoperation training system.**

Scenario	Nb. of experiments (Total 40)	Driving method	TC	DR	Conection type	Bandwidth
1	8	*Joystick*	Manaus	Manaus	Local	100 Mbps
2	8	*Eye-tracker*				
3	8	GHMI				
4	8		Campinas		Internet	70 Mbps
5	8		Uberlândia			40 Mbps

objective. This work is a pilot test and the experiments were divided into three parts.

First, the concept was to test a teleoperation system with multiple driving methods. All the commands from all control interfaces must be translated to electrical signals to control the wheelchair properly. Therefore, it was necessary to create scenarios with the developed driving methods. The scenario characteristics are presented in Table 3.

Second, the idea was to test the proposed automatic command counting algorithm. To accomplish that, all the command data files generated from the experiments were submitted to the proposed algorithm, and the results were presented. The idea was to test if, regardless the control interface, the algorithm could work and give the number of commands as an output.

FIGURE 14. **Path for the teleoperation training experiments.**

Third, the objective was to test the system using long-distance teleoperation to control the EPW. The study was to compare performances through local and Internet connections, and moreover, to verify if the long-distance delay considerably affected the use of the system. Thus, there were scenarios where the TC and DR were in the same city, and in different cities, which are presented in Table 3. For the long-distance teleoperation, the requirement was that both TC and DR had a wired broadband connection to the Internet. The bandwidth characteristics of the Internet connection are also presented in Table 3.

Different scenarios were created to test those concepts. The first, second, and third scenarios were based on the joystick, eye-tracker and GHMI driving methods, respectively. The fourth and fifth were based on GHMI considering long-distance teleoperation over the Internet. The linear distance between the TC and DR in scenario 4 was approximately 2596 km, and 2172 km in scenario 5. Table 3 shows a general view of the experiment configurations. Furthermore, every scenario had the same path to be completed by the training user, as presented in Figure 14.

The total number of experiments is 40, in which every scenario was performed 8 times. In all experiments, the command data, the RTT, and the time spent to finish the course was collected and obtained automatically by the difference of timestamps from the beginning and end of the experiment.

Figure 15 presents the user's view when practicing over the GHMI. It is possible to see the First-person View (FPV) camera, as well as the Third Person View (TPV). The GHMI is in the bottom right corner of Figure 15.

Figure 16 presents the joystick control interface. It is possible to see the original EPW joystick adapted with the embedded system (Arduino), and the video streaming from both cameras.

Figure 17 presents practice with the eye tracker control interface. It is possible to see the eye tracker (Tobii 4c) attached to the computer screen.

Figure 18 (a) shows the overview of average time spent on the forty experiments (eight in each scenario). Furthermore, Figure 18 (b) presents the average number of commands.

Figure 19 (a) presents the time spent on the experiments of each scenario. Further, Figure 19 (b) shows the number of commands throughout the courses.

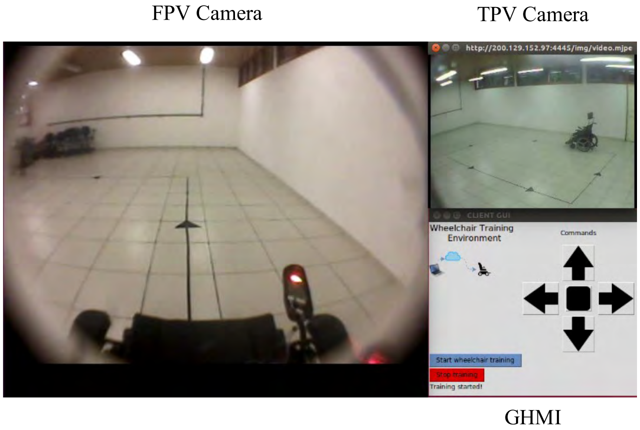


FIGURE 15. Teleoperation by the GHMI.

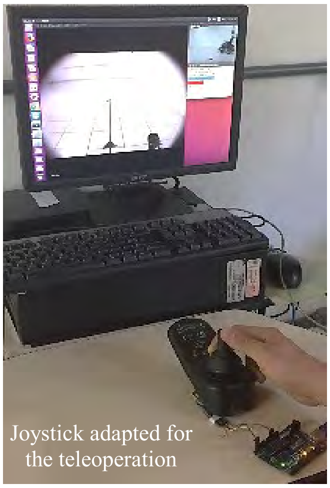


FIGURE 16. Experiment with the teleoperation by the joystick control interface.

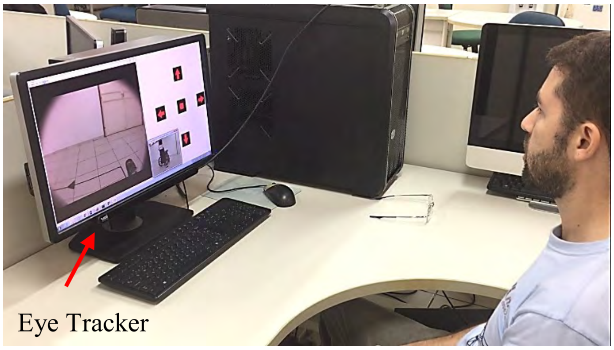
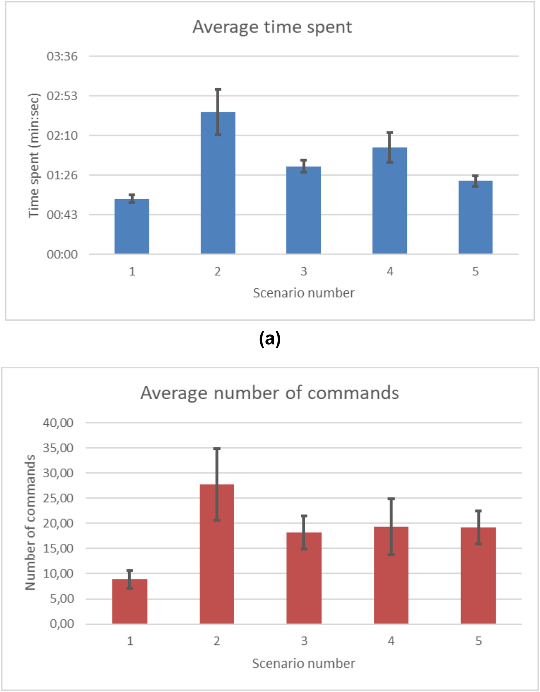


FIGURE 17. Experiment with teleoperation by the eye tracker control interface.

Table 4 provides the details of the statistical data of time spent throughout the experiments. Table 5 presents the statistics of the number of commands from all scenarios. Table 6 shows the statistical delay data from all experiments.

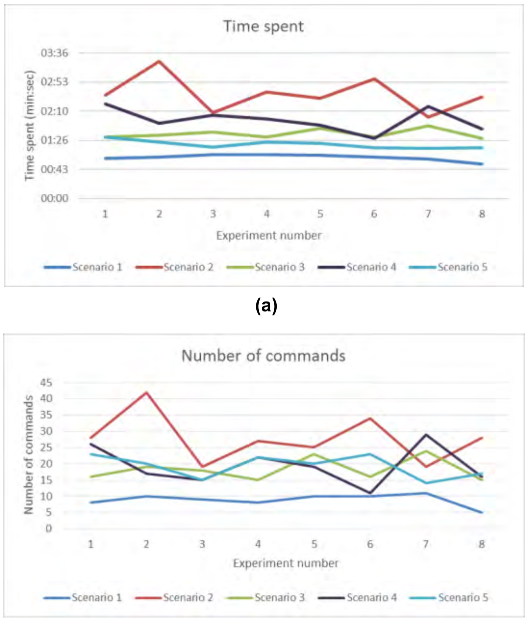
Figure 20 presents the histograms of the delay from the teleoperation over the Internet (scenarios 4 and 5).



(a)

(b)

FIGURE 18. (a) Overview of the average time spent with standard deviation (SD). (b) Average number of commands and SD.



(a)

(b)

FIGURE 19. (a) Time spent on the experiments. (b) The number of commands for the experiments.

Figure 21 presents a plot of the delay samples from all experiments performed in scenarios 4 and 5.

V. DISCUSSION

This section presents the inferred aspects obtained from the experimental results, followed by an association with related works.

TABLE 4. Statistical data of time spent on all scenarios.

	Time spent (min:sec)				
Scenario	AVG	±	SD	Max.	Min.
1	01:01	±	00:04	01:05	00:51
2	02:35	±	00:25	03:24	02:01
3*	01:36	±	00:07	01:48	01:29
4*	01:57	±	00:16	02:20	01:29
5*	01:20	±	00:06	01:31	01:14

* Mean values significantly differed according to One-Way ANOVA, $p < 0.05$ and $p = 0$. The comparison was performed only between scenarios 3, 4 and 5.

TABLE 5. Statistics of the number of commands of all scenarios.

	Number of commands				
Scenario	AVG	±	SD	Max.	Min.
1	8.88	±	1.76	11	5
2	27.75	±	7.10	42	19
3*	18.25	±	3.31	24	15
4*	19.38	±	5.59	29	11
5*	19.25	±	3.31	23	14

* Mean values did not significantly differ according to One-Way ANOVA, $p < 0.05$ and $p = 0.831$. The comparison was performed only between scenarios 3, 4 and 5.

TABLE 6. Statistics on the delay of all experiments.

	Delay - RTT (ms)				
Scenario	AVG	±	SD	Max.	Min.
1	2.24	±	1.01	23.10	1.49
2	1.89	±	3.38	49.41	0.99
3	2.07	±	4.05	92.23	1.44
4	85.27	±	24.49	532.06	76.68
5	130.12	±	8.12	266.62	122.20

The results showed specific characteristics for each driving method. For instance, the joystick (scenario 1), as a reference driving method, obtained the minimum average time spent (01 min: 01 sec ± 04 sec), and the minimum average number of commands (8.88 ± 1.76). The eye-tracker (scenario 2) had the maximum average time spent (02 min:35 sec ± 25 sec) and a higher average number of commands (27.75 ± 7.10). This performance level using an eye-tracker control interface is acceptable considering that driving through eye movements is not an easy task and it might be the only option for some users with severe disabilities.

The influence of the long-distance communication delay was one main aspect evaluated during the training. A comparison between training using the GHMI from a local and an Internet connection was performed (scenarios 3, 4 and 5). As expected, the average delay in local connection scenario 3 (2.07 ms ± 1.01 ms), was significantly lower than Internet scenario 4 (85.27 ms ± 24.49 ms), and Internet scenario 5 (130.12 ms ± 8.12 ms).

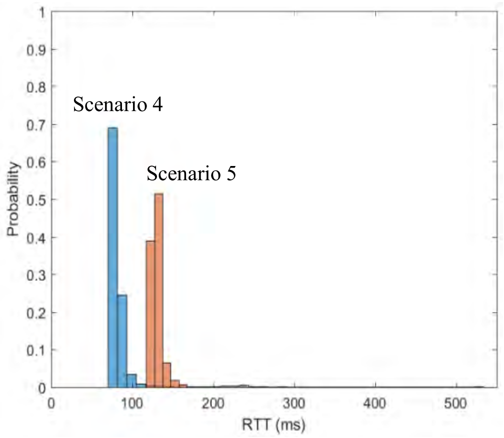


FIGURE 20. Histograms of the delay from the experiments over the Internet.

Comparing the Internet scenarios, the average delay in scenario 4 was lower than scenario 5, despite the latter being closer to the DR, this occurred due to the larger bandwidth of scenario 4 (70 mbps) than scenario 5 (40 mbps). Although, there were high delay values in both Internet scenarios 4 (532.06 ms) and 5 (266.02 ms), with a significantly low probability (near zero percent), which is possible to observe in Figure 20.

Therefore, comparing the driving performance from the local connection (scenario 3) and Internet (scenarios 4 and 5), scenario 5 had the lowest average time spent (1 min:20 sec ± 06 sec), and the others (1 min:36 sec ± 07 sec), and (1 min:57 sec ± 16 sec). The difference of time spent in those scenarios might have occurred due the different levels of ability of the practicing users (different person on each scenario), on which some took less time stopping the EPW during curves and throughout the course. However, the average number of commands were very similar in scenario 3 (18.25 ± 3.31), scenario 4 (19.38 ± 5.59), and scenario 5 (19.25 ± 3.31), representing practically the same value. These similarities of the number of commands might have happened due to similar strategies of the practicing users during the course, for instance, every user needed to follow the same path, so, turn left, and go forward at the same positions. Therefore, since there were similarities between the local and Internet performances, in relation to the number of commands, it is suggested that the Internet delay did not considerably affect the use of the training system. Hence, these results contribute to a better understanding of the use of teleoperation for EPW training, suggesting that is possible to practice by distance despite the Internet delay.

Many other authors created training environments for EPW, as mentioned in the related work section. Their approach was focused on virtual environments with the joystick as a driving method. However, this work proposed a training environment with multiple driving methods.

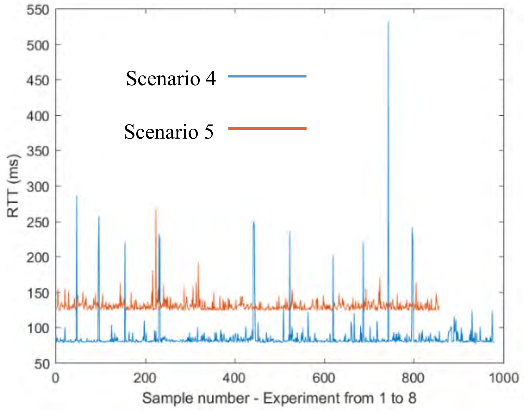


FIGURE 21. Plot of all delay samples from the experiments performed over the Internet.

TABLE 7. The contrast between related works and this proposal.

Reference	**Training environment**	**Authentic physical world behavior**	**Multiple driving methods**
[5]	Virtual	No	No
[4]	Virtual	No	No
[7]	Virtual	No	No
[8]	Virtual	No	No
[9]	Virtual	No	No
This Proposal	**Teleoperation over the Internet**	**Yes**	**Yes**

Another different method suggested and evaluated in this work was to use a real teleoperated wheelchair, therefore making easier the problem of representing the physical behavior of the wheelchair. Table 7 presents this contrast with related works.

The importance of having multiple driving methods in a new user EPW training environment was verified because each method attends to a specific type of user. Further, it was also demonstrated that despite the Internet delay, it is possible to practice by long distance. Moreover, it was tested that despite having low cost, the proposed architecture worked properly, which is an important aspect of making it easier to replicate the system for developing countries, such as Brazil. For instance, to replicate the TC, the necessary equipment and material would be a computer, broadband Internet, and at least one driving method. In addition, various users could use the same TC to practice. Furthermore, it would be possible for multiple TCs to use the same DR. Finally, this system architecture is flexible enough to include other driving methods, following the software structure of the GHMI.

VI. CONCLUSION

The purpose of this study was to investigate a more realistic approach to train new users of EPW. The proposed architecture was tested and it was possible to use remote messages to drive the EPW since commands sent from the TC to DR were translated to electric signals that moved the EPW according to the proposed protocol. Considering the long-distance teleoperation, the Internet delay did not significantly affect the use of the training system, showing that it is possible for users to practice even with DR and TC located in different cities. Then, there is the possibility to replicate the system with low-cost by creating new TCs using at least one DR.

Furthermore, it was confirmed that it is possible to make easier the problem of representing wheelchair physical behavior, which was mentioned by related works of virtually simulated training environments. Hence, these results contribute to a better understanding of the usage of teleoperation for the training of new users of electric powered wheelchairs. Future research will concentrate on including more driving methods in the proposed architecture, due to its flexibility. In addition, the authors will also focus on implanting the system in hospitals and clinics and creating new TCs to test the system on users with diverse types of disabilities.

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