Enhancing Accessibility: Head Motion Controller Integration in Virtual Training for Assistive Technology

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Abstract. Electric wheelchairs provide valuable assistance to individuals with paraplegia. However, they often fall short in catering to those with more severe impairments, such as quadriplegia, where individuals are unable to move any part of their body except their head due to age or illness. The objective of this project is to address this gap by developing a solution that enables wheelchair movement through head motion.

Our proposed solution involves integrating an accelerometer onto a cap worn by the patient to accurately track head movements. By processing the data from the accelerometer, we can precisely recognize these movements. Subsequently, this information is utilized to control stepper motors, which in turn manipulate the joystick of an electric wheelchair.

Through this innovative approach, we aim to empower individuals with quadriplegia to navigate their environment with greater independence and mobility, thereby enhancing their quality of life.

Keywords: Paraplegian, rehabilitation, Wheelchair, Virtual Reality Training
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1 INTRODUCTION

Quadriplegia, a condition wherein individuals lose the ability to use any of their extremities, can stem from various causes such as strokes, arthritis, degenerative bone and joint diseases, paralysis, birth defects, accidents, or age-related factors [9]. These individuals face significant challenges in performing daily tasks like feeding, using the toilet, and moving around [5]. Depending on the severity of their condition, they may rely on a range of medical devices to maintain some level of mobility [6].

Recognizing the vital role mobility plays in enhancing their quality of life, our project aims to design a system that grants independent mobility to individuals with severe disabilities. Our prototype has been developed and rigorously tested to ensure its efficacy in assisting users.

2 STATE OF THE ART

Recent advancements in assistive technology have focused on improving the accessibility and usability of devices for individuals with mobility impairments. Virtual training environments have gained prominence as they provide a safe and controlled space for users to learn and practice using assistive devices. Studies have shown that immersive virtual reality (VR) training can significantly enhance the user's ability to operate wheelchairs and other mobility aids [11], leading to better real-world performance and increased confidence [12], [2].

Head motion controllers are increasingly being integrated into assistive devices to provide hands-free operation. These controllers use accelerometers and gyroscopes to detect head movements, translating them into control signals for various devices. This technology has been found effective in providing users with greater autonomy and ease of use, particularly for those with limited upper limb mobility .

3 HEAD MOTION CONTROLLER

The prototype comprises a digital system, consisting of an accelerometer and a microcontroller, along with a mechanical actuator. The accelerometer captures data on head motion, which is then processed by an algorithm executed within the microcontroller. This processed data instructs the mechanical actuator to position the wheelchair joystick according to the user's commands.

Furthermore, to facilitate the user's acclimatization to the system, we've developed a Unity [10] application divided into two sections: tutorial and free-mode. The tutorial guides users through fundamental head movements, helping them understand the system's functionalities, while the free-mode allows them to explore a virtual environment without constraints.

By seamlessly translating user head movements into electric wheelchair [4],[3], joystick positions and providing intuitive training through the Unity application, our project aims to significantly enhance the independence and confidence of individuals living with quadriplegia. Figure 1 shows the project block diagram and Figure 2 shows the joystick motion system final position.

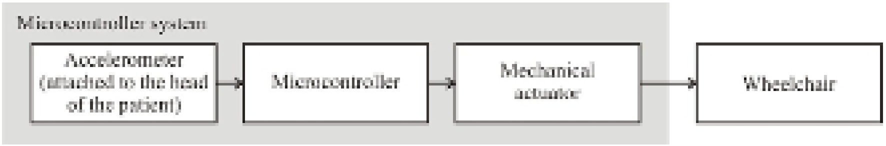


Figure 1: Project block diagram

4 MOVEMENT RECOGNITION

Motion recognition involves a receiver identifying a user's movements. In our context, we employ an accelerometer mounted on a cap worn by the patient to measure head position. When the head exceeds a certain threshold angle, the accelerometer ADXL335 processes this information as can be seen from Figure 3

The ADXL335 sensor, a capacitive accelerometer, operates on the principle that applying acceleration changes the capacitance inside the sensor. This change is translated into an electric signal, enabling the measurement of object acceleration. With three axes of sensitivity, it can detect accelerations in all directions.

Featuring six pins and an integrated chip, the ADXL335's VCC pin powers it, while X-out, Y-out, and Z-out measure acceleration along their respective axes. The GND pin serves as the ground.

The patient's potential head positions are divided into sectors, each yielding a zone-number output when entered. (Figure 4)

Figure 2: Joystick motion system

A segment of the Arduino code aids in understanding the process. When the patient surpasses a threshold angle, variables "a" or "b" assume defined values. Integer values are used as Unity's maximum Arduino input is limited to 128.

Since simultaneous signals cannot be sent, a variable "somma" consolidates information on the X-Y position region.

5 COMMAND

We have chosen to control the wheelchair through the joystick head based controll approach because the rehabilitation center with which we collaborate utilizes a variety of wheelchair models. This diversity in wheelchair types necessitates a control mechanism that is universally compatible and adaptable. The joystick-based control method meets these requirements effectively, providing a standardized interface that can be integrated with multiple wheelchair systems regardless of their specific configurations.

By adopting the joystick approach, we ensure that our solution can be implemented seamlessly across different wheelchair models, enhancing its practicality and ease of use in the real-world settings of the rehabilitation center. This uniformity simplifies the training process for both users and staff, as they only need to familiarize themselves with one control method. Furthermore, it reduces the need for specialized equipment or modifications for each wheelchair, leading to cost savings and easier maintenance.

The joystick control also offers a familiar and intuitive interface for users, many of whom may already have experience with similar systems. This familiarity can shorten the learning curve and increase user confidence and comfort, which are critical factors in rehabilitation settings. Overall, the joystick approach provides a versatile, user-friendly, and cost-effective solution that aligns well with the diverse needs of the rehabilitation center and its patients. Depending on the combination of the different movement of the head it's possible to have different commands for the wheelchair:

- Activation: as shown in the following figures the activation requires a series of consequently movements of the head. (Figure 5)

Figure 3: Accelerometer ADXL335

This sequence can be better visualized with the Arudino code:

The variable called "conto" permits to make the procedure subsequently while the parameter "a" is related to the range of the angle of the head. Once the activation step is completed a state of still is reached and a new possible set of commands can be done:

- Turn right/left:

- Go forward:

Once the condition to go forward is active it's possible simultaneously to turn right/left.

- Deactivation: if it's on the state of going forward and the command deactivation is done, it comes back to a state of still. In all the other case it comes back to a state 0 (state that requires again the activation process).

- Backward: in order to activate this command it's necessary to be in the state 0. Then a series of movements are required:

Once this first step is done, every times that the head is turned backwards the wheelchair moves backwards.
In order to deactivate this command the head is moved forward and the state becomes 0.

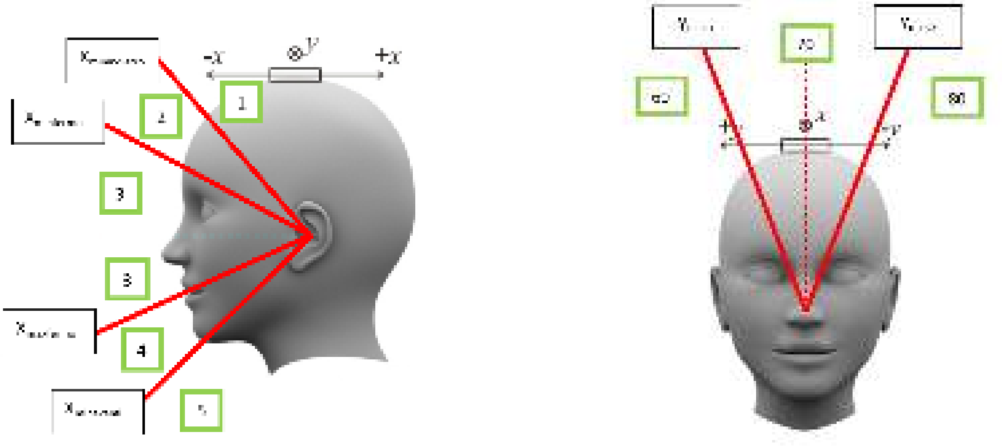
Like the forward command also the backward needs a procedure which is subsequent. This is permitted by the variable "memretro" that increases of 1 every time that a step is completed.

6 PHYSICAL PROTOTYPE

To facilitate movement, a mechanical system equipped with two stepper motors has been developed. This system enables precise control over the displacement of the joystick.

This mechanism allows movement of the joystick in four main directions: forward, backward, left, and right. The motion is facilitated by a series of gears, as depicted below.

The initial gears facilitate shaft rotation, while the subsequent ones, acting like a rack and pinion, enable forward and backward movement. All gears are fabricated using a 3D printer.



(a) Threshold on X-axis. (b) Threshold on Y-axis.

Figure 4: Threshold angles

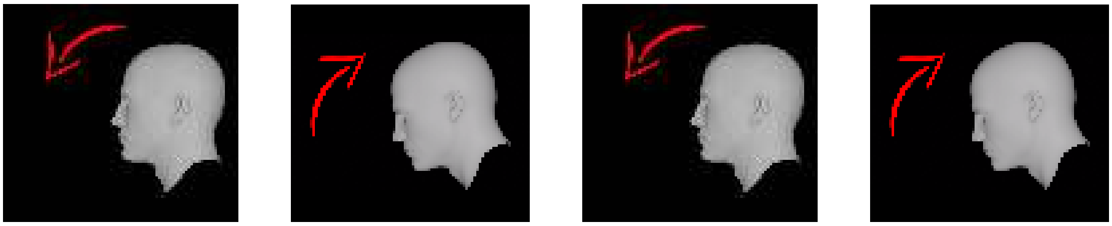


Figure 5: Activation sequence

- Spur Gears: These are created using a Sharebot 3D printer to transmit rotation from the motor to the main shaft. Special grooves are designed on both gears to facilitate coupling with the main shaft, and with a potentiometer and stepper motor for the upper gear.

  The use of spur gears is integral to the design of our head motion-controlled wheelchair system. Spur gears are chosen for their simplicity, efficiency, and reliability, making them ideal for applications requiring precise and consistent motion transfer.

  Spur gears are among the simplest types of gears, characterized by their straight teeth and parallel shaft alignment. This straightforward design not only simplifies the manufacturing process but also ensures ease of maintenance and replacement. The simplicity of spur gears contributes to their durability and long operational life, which is crucial for applications like wheelchair control systems that require high reliability.

  Spur gears are highly efficient at transferring motion and power between shafts. They exhibit minimal energy loss due to friction, making them suitable for applications where energy efficiency is critical. This efficiency is particularly important in battery-powered systems, such as our wheelchair, where maximizing the usage time between charges is a priority.

- Circular Rack and Pinion: These are also created with a Sharebot 3D printer to transmit power for

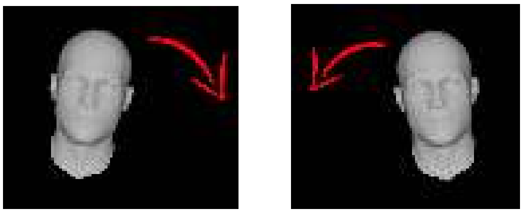


Figure 6: Turning

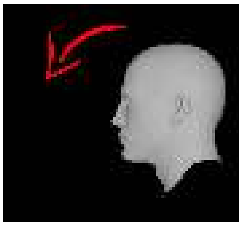


Figure 7: Forward

shaft translation. To ensure coupling with the circular rack, four holes are designed on the shaft, with threaded grains utilized for connection. (Figure 11)

- Main Shaft: A commercially available PVC shaft is used, machined using a CNC machine "Charly4U" to create four holes for locking the circular rack and a groove. This groove allows coupling with the rotational gear when the shaft translates, ensuring the transfer of rotational moment. (Figure 12) The main shaft is a critical component in our head motion-controlled wheelchair system, serving as the central axis around which other mechanical parts operate. It is responsible for transmitting rotational motion from the motor to the spur gears, which then translate this motion to the joystick, enabling precise control of the wheelchair

- Regulation System: Implemented to customize for different wheelchairs, this system allows height and distance adjustments of the shaft in relation to the joystick position. (Figure 13)

  At the heart of the regulation system is an initial calibration process designed to personalize the wheelchair's response to the user's specific needs. This involves:

  Manual Adjustment: At the start, the system requires manual calibration where the user, starting from a neutral head position, moves their head to various positions corresponding to the desired joystick movements. These positions are recorded and stored as threshold values.

- Stepper Motors: Two NEMA 17 stepper motors are used for motion, powered by a 12 V battery (VELAMP 23724). These motors allow precise control over positioning but require continuous power to maintain position. (Figure 14)

- Potentiometers: These devices vary the position of a sliding contact across a uniform resistance. They are used to adjust the output voltage, facilitating control over joystick movement.

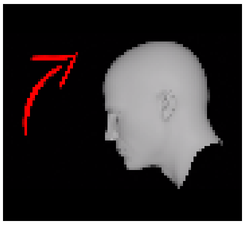


Figure 8: Deactivation

Figure 9: Digital Prototype

- Case: Consisting of six elements, the case is designed with 3D printers to accommodate all system components while maintaining a compact design.

- Battery: Power is supplied by a rechargeable 12 V battery (VELAMP 23724).

All printed components are made of PLA (Polylactic Acid), a biodegradable thermoplastic derived from renewable resources like cornstarch or sugarcane.

This comprehensive system allows for precise control over the wheelchair's joystick, facilitating movement in all directions and enhancing the user's mobility and independence.

7 MOTOR CONTROL

The stepper motors are managed via specialized drivers connected to an Arduino through a CNC Shield V3.0.

At the outset, a calibration is necessary to determine the maximum displacement and rotation of the shaft. Threshold values of the potentiometers must be defined. While this can be adjusted directly within the software, an automated system was implemented for convenience and quicker setup. This system is activated by a simple switch.

During calibration, starting with the shaft in the center position, the operator manually moves it to the desired position of the joystick (forward/backward and left/right), which is then stored by the system.

Once this calibration step is completed, the motor can be operated. Understanding the motor control process is facilitated by examining the Arduino code.

Upon recognition of head movement, a variable called "opz" assumes a specific value. The switch function then activates different sub-functions based on these "opz" values.

For instance, when "opz=1", the "forward" function is invoked. This function enables the movement of the shaft until the threshold value is reached. If the head returns to the normal position, the "controllointerrompiTrasl" function is activated, which halts the shaft movement and is continuously monitored.

Similar analog functions are implemented for other movements.

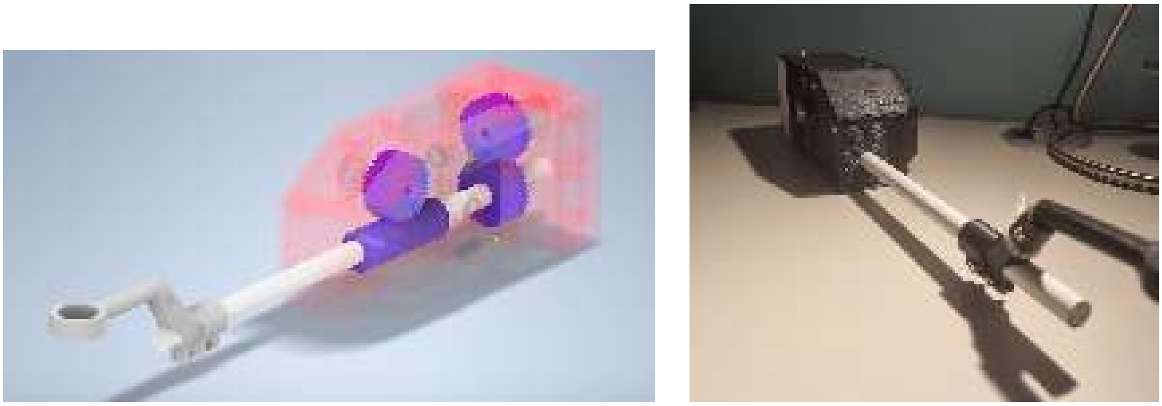


Figure 10: Physical Prototype

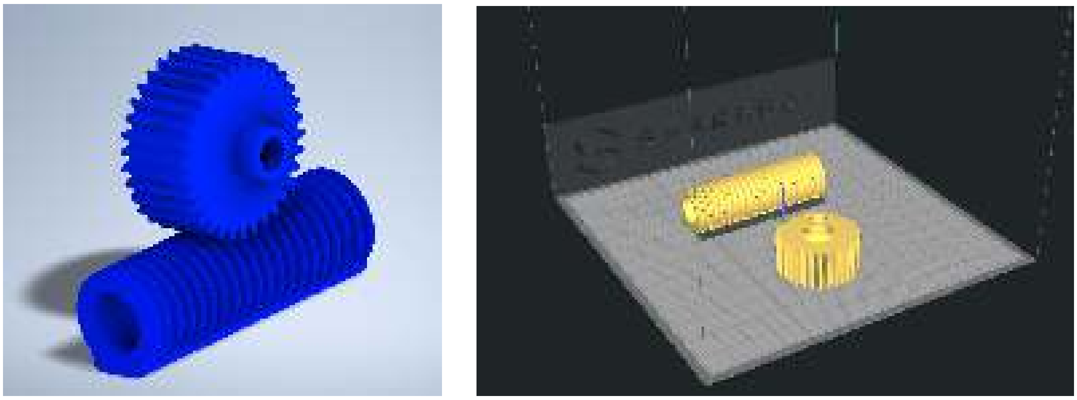


Figure 11: Circular Rack and Pinion for Shaft Translation

8 VIRTUAL TRAINING

The virtual training application, developed using the Unity engine, offers a highly immersive and interactive environment that significantly enhances the user's learning experience. Unlike traditional training methods, our system provides real-time feedback and adaptive learning paths tailored to the user's progress, which is a considerable advancement over static and non-interactive training manuals or videos.

Moreover, the integration of a head motion controller as the primary input device is a novel approach in the context of assistive technology training. This allows users to practice in a hands-free manner, closely mimicking real-world scenarios where they would rely on such controls. The use of Unity's advanced graphics and physics engines ensures a realistic simulation, providing users with a safe space to practice without the risks associated with real-world training.

Virtual training serves as a crucial component in the development and implementation of assistive technologies, particularly for individuals with mobility impairments. Here are several reasons why virtual training is important in this context:

- **Safe Environment**:

  Virtual training provides a safe and controlled environment for users to practice using assistive devices without the risk of injury. This is especially important for individuals who may have limited mobility

Figure 12: Manufacturing of the Shaft

Figure 13: Regulation System

or physical strength, allowing them to learn and familiarize themselves with the technology in a secure setting.

- **Accessibility**: Virtual training can be accessed from anywhere with an internet connection, making it highly accessible to users regardless of their location or physical abilities. This ensures that individuals in remote or underserved areas have access to training resources and can benefit from assistive technologies.
- **Repeatable Practice**: Virtual training allows users to repeat training exercises as many times as needed to improve their skills and confidence. This repetition is essential for mastering the use of assistive devices and can lead to better overall performance in real-world scenarios.
- **Customization**: Virtual training platforms can be customized to accommodate users with different levels of ability and learning styles. This flexibility allows for personalized training experiences tailored to the specific needs and preferences of each individual user.

Virtual training is developed using Unity, a versatile graphics engine utilized for various interactive content, including video games, architectural visualizations, and real-time 3D animations [1], [7], [8].

The Unity project comprises several key components:

- **Main Menu**: The initial scene featuring three buttons for tutorial, free-mode training, and exit options. Each button is associated with a script, enabling seamless navigation to the corresponding scene. (Figure 15)

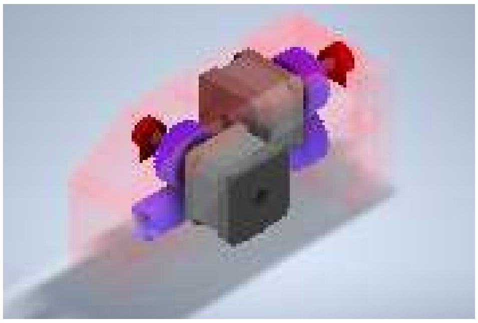
 

Figure 14: Stepper Motors

Figure 15: Main menu

- **Tutorial**: Consists of multiple scenes guiding users through various head movements required to operate the wheelchair. Each scene presents instructions and a video demonstration. Completion of each operation triggers the transition to the next tutorial level. (Figure 16)
- **Free-mode**: Enables users to navigate freely in a virtual environment, enhancing familiarity with head movements and providing obstacle training. The scene presents a first-person view, with text prompts indicating possible movements. (Figures 17 and 18)
- **Exit Menu**: Activated by pressing the "esc" key, this menu offers options to restart from the initial position, return to the main menu, or quit the application. It also allows adjustments to audio and video settings.

9 PILOT TEST

To rigorously assess the effectiveness and user-friendliness of the VR training application, a usability test was performed. A usability test provides a quantitative measure of the overall usability of a system based on user feedback.

Figure 16: Forward scene

Figure 17: Free-mode

9.1 Participants

A group composed of 13 students from the bachelor and master degree program, participated in the usability testing. This diversity ensured that the feedback encompassed a broad range of perspectives and user experiences, making the evaluation more robust and generalizable.

9.2 Measures

Quantitative and qualitative data were collected:

System Usability Scale (SUS): After the training sessions, trainees filled out the System Usability Scale (SUS) questionnaire, which is designed to capture user perceptions across ten statements related to various aspects of usability. Participants rated each statement on a five-point Likert scale. This approach provided a comprehensive assessment of the application from the users' perspective.

The SUS covered three critical aspects of usability:

Ease of Use: How straightforward and intuitive the trainees found the application. Learnability: The ease with which new users could learn to navigate and use the application effectively. Satisfaction: Overall satisfaction with the application, encompassing enjoyment and perceived value. Detailed Qualitative Feedback: Collected through open-ended questions, further supplemented the quantitative data, offering insights into specific pain points and user experiences.

Data Analysis The SUS scores were analyzed to generate an overall usability score for the training application. Each trainee's responses were converted into a score ranging from 0 to 100, with higher scores indicating

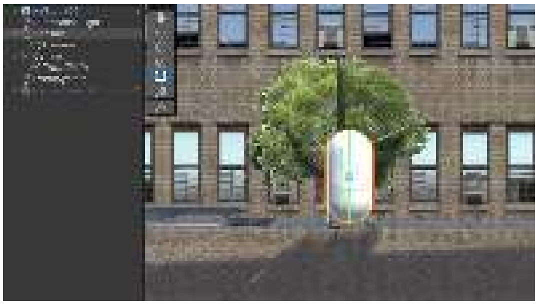


Figure 18: Capsule

Figure 19: Pause menu

better usability. The average SUS score was then calculated. The qualitative feedback was analyzed to gain valuable insights into the strengths and weaknesses of the application.

Results Preliminary results indicate positive feedback from trainees regarding the usability and effectiveness of the training application. The overall SUS score was 63.65, surpassing industry standards and reflecting high levels of user satisfaction and ease of use. Figure 20 shows the results in the SUS questionnaire. Furthermore, the analysis of the SUS scores revealed both strengths and areas for improvement within the training application. From the qualitative feedback, trainees reported increased engagement and confidence in responding to emergency situations, highlighting the potential of AR technology in enhancing emergency training and management. The qualitative data also provided insights into how to improve the application. Considering the usability problems encountered, the need emerged to improve the user interface and make the overall training experience easier to understand and usable. These changes were made following an iterative development process, which ensures that the application evolves in response to user needs and feedback, ultimately leading to a more effective and user-friendly training tool.

10 CONCLUSIONS

In conclusion, the development of a system aimed at providing independent mobility for individuals with severe disabilities marks a significant step towards enhancing their quality of life. Through the integration of innovative technologies and thoughtful design considerations, this project has laid the foundation for empowering individuals with limited mobility to navigate their surroundings with greater freedom and autonomy.

Statement	1	2	3	4	5
1. I think that I would like to use this system frequently		2	3	6	2
2. I found the system unnecessarily complex	2	6	3	2	
3. I thought the system was easy to use		2	4	4	3
4. I think that I would need the support of a technical person to be able to use this system	1	2	2	7	1
5. I found the various functions in this system were well integrated		1	3	8	1
6. I thought there was too much inconsistency in this system	1	6	5		1
7. I would imagine that most people would learn to use this system very quickly	1			9	3
8. I found the system very cumbersome to use	6	6	1		
9. I felt very confident using the system		4	2	5	2
10. I needed to learn a lot of things before I could get going with this system	1	3	5	2	2

Dove 1= Strongly Disagree e 5 Strongly Agree

Figure 20: SUS results: the numbers in the table show how many participants responded with a certain score

The implementation of an accelerometer-based head motion recognition system, coupled with a mechanical actuator to control the wheelchair joystick, demonstrates the feasibility of translating user gestures into meaningful actions. By using the power of Arduino microcontrollers and stepper motors, we've created a prototype that bridges the gap between user intent and wheelchair movement.

Furthermore, the addition of a virtual training environment using Unity software offers users a safe and interactive platform to familiarize themselves with the system's operation and refine their mobility skills. This not only enhances user confidence but also accelerates the learning curve for adapting to the new assistive technology.

While this project has achieved notable progress, there remain areas for refinement and future development. Addressing challenges related to motor power, threshold calibration, and wheelchair maneuverability are crucial for optimizing system performance. Additionally, exploring alternative sensor technologies, motor types, and wheelchair configurations could unlock further improvements in functionality and user experience.

In essence, this project serves as a prove to the potential of technology to empower individuals with disabilities, enabling them to lead more independent and fulfilling lives. By continuing to innovate and collaborate, we can strive towards a future where assistive technologies seamlessly integrate into daily life, breaking down barriers and fostering inclusivity for all.

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