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A VR-BASED UPPER LIMB EXOSKELETON FOR NEUROMOTOR REHABILITATION

BY

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Abstract. This paper presents a novel upper limb rehabilitation system for stroke patients, combining a patient-specific exoskeleton with an integrated Augmented Reality (AR) platform. By leveraging advanced technologies such as gesture recognition and AR tools (e.g., Microsoft HoloLens), the system aims to enhance functional recovery and user engagement. A custom-designed exoskeleton prototype has been developed and tested, emphasizing precise joint trajectory control, kinematic accuracy, and adaptability to individual user needs.

Validation has been conducted through bench tests and human-in-the-loop experiments, focusing on control performance, ergonomic design, and safety. Moreover, the development and testing of the AR-assisted exoskeleton system were carried out with continuous input from a physical therapist, ensuring that clinical expertise was embedded from the conceptual stage onward. These results support future integration into customized rehabilitation protocols for better

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neurofunctional outcomes by confirming the viability and clinical potential of intelligent, user-adaptive exoskeleton systems.

Keywords: upper limb exoskeleton, neuromotor rehabilitation, HoloLens2, upper limb assistive devices.

1. Introduction

The combination of immersive technologies and wearable robotics is causing a significant shift in the field of neuromotor rehabilitation. Exoskeleton-like devices enhanced by Augmented Reality (AR) platforms like the Microsoft HoloLens 2 are among the most exciting developments. These systems offer a highly interactive, visual, and responsive therapeutic environment in addition to helping and rehabilitating patients with motor impairments, such as those brought on by stroke, spinal cord injury, or neuromuscular disorders. With the help of voice commands, gaze tracking, and simple gestures, the HoloLens 2's hands-free, spatially aware augmented reality interface allows for the real-time visualization and control of robotic systems (Dobkin, 2021). It performs a variety of functions when incorporated into rehabilitation exoskeletons, including remote therapist supervision, biofeedback visualization, virtual guidance, command input, and movement intention detection. During training sessions, this method promotes precise control of motor tasks, neuroplasticity stimulation, and user engagement (Maciejasz *et al.*, 2014).

Specifically, HoloLens 2 allows for a natural and immersive human-machine interface (HMI) that does away with the need for external monitors or heavy physical controllers. While using the exoskeleton to perform assisted movements, patients can engage directly with their virtual environment while getting real-time feedback in the form of progress indicators and holographic cues. Additionally, this integration enables context-aware control systems, in which the AR interface adjusts to the movement patterns, behavior, and rehabilitation objectives of the patient. With an emphasis on upper limb rehabilitation, this study investigates the design, operation, and experimental validation of such an augmented exoskeleton system. The HoloLens 2 interface is used to implement and assess a variety of control strategies, such as gesture-based actuation and joint trajectory tracking. To evaluate control accuracy, responsiveness, and user experience, and ultimately improve clinical rehabilitation outcomes, the system is tested on both healthy users and simulated patient scenarios (Cuffaro *et al.*, 2023).

2. The main features of the designed upper limb exoskeleton

The exterior lines and those under the head should be double lines. Since the advent of mechatronic systems, intelligent human-machine interfaces, and

augmented reality in recent decades, technology-assisted medical rehabilitation has grown significantly (Borghese, 2020). In this regard, exoskeletons for the upper limbs offer a novel way to help patients with neurological disorders like stroke, traumatic brain injury, or spinal cord injury regain their motor abilities. One exoskeleton, designated EXOSLIM (Serea *et al.*, 2015), developed in our SCECM research laboratory (Faculty of Electrical Engineering, TUIASI), aims to provide accurate and adaptable biomechanical assistance during rehabilitation exercises, as illustrated in Fig. 1.

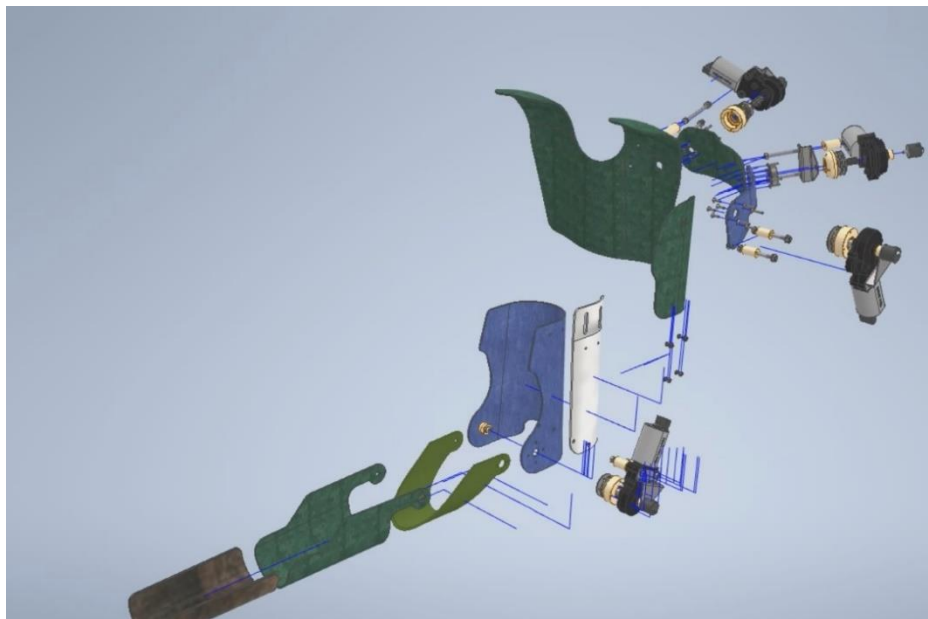


Fig. 1 – The 3D design of the EXOSLIM system.

An exoskeleton's ability to regulate its position is crucial to its therapeutic efficacy. Joysticks, touch interfaces, or pre-programmed protocols are typically used to accomplish this control, which may restrict the therapist's flexibility and the patient's degree of involvement. A new paradigm of immersive, natural, and intuitive interaction is introduced by the use of augmented reality through gadgets like the HoloLens 2, which has major advantages for the healing process. An active upper limb exoskeleton called EXOSLIM was created specifically for patients with hemiplegia, hemiparesis, or other motor impairments (Popescu *et al.*, 2017).

The exoskeleton's joints are powered by four DC motors that are controlled by two H-bridge drivers. Each driver can provide a continuous current of 10 A and a peak current of up to 15 A. The DC motors are powered by pulse-width modulation (PWM) impulses at a frequency of 50 Hz. A pulse width of

1.5 ms represents a neutral condition that locks the motor shaft. Increasing the pulse width over 1.5 ms causes clockwise rotation, with a maximum speed at 2.5 ms.

Reducing the pulse width below 1.5 ms causes counterclockwise spinning, with the maximum speed corresponding to a 0.5 ms pulse width (Serea, 2015). Control signals for the two *Sabertooth* drivers are generated by an *SSC-32* servo controller, which is interfaced with a PC via an *RS232* serial connection.

To obtain real-time joint position feedback, 10 k Ω linear potentiometers are mounted on each motor shaft. These potentiometers are powered with a regulated 5 V supply provided by the controller's internal voltage regulator (Serea *et al.*, 2015).

To provide mobility that closely resembles the natural movement of a human limb, it incorporates electric actuators, position sensors, haptic feedback, and a lightweight composite structure. The system allows the wrist, elbow, and shoulder joints to be trained, and the degrees of freedom can be changed to suit the patient's requirements (Serea *et al.*, 2013; Poboroniuc and Irimia, 2020).

This exoskeleton's ability to work with external control interfaces is a key feature that makes it a perfect fit for integration with cutting-edge technologies like augmented reality or voice and gesture-based control. (Poboroniuc *et al.*, 2023).

By superimposing digital elements on top of the actual physical environment, Microsoft's HoloLens 2 augmented reality device provides users with an interactive experience. With its depth sensors, hand and eye tracking cameras, and sophisticated audio system, the HoloLens 2 allows users to interact naturally with applications that are shown in three dimensions. HoloLens 2 can act as a mediator between the therapist and the exoskeleton during rehabilitation, offering a hands-free means of supervision and control.

Through gesture or voice command recognition, the therapist can adjust the operating parameters of the exoskeleton in real time, without interrupting the patient's activity (Roman *et al.*, 2020). Additionally, the patient can be actively involved in interactive exercises, which increases motivation and engagement.

3. Interactive System Development in Unity for HoloLens 2 Integration

Once the *.FBX* file is prepared, the software development phase begins.

At this stage, the exoskeleton evolves from a static 3D model into an interactive, functional element within a virtual environment built using **Unity**—a powerful 3D game engine widely used in both industry and research (Ungureanu, 2020). Working in conjunction with **Visual Studio**, Unity provides the framework needed to program the exoskeleton's behavior, define the interaction logic between its mechanical components, and enable user interaction—whether by therapists or patients—through **HoloLens 2** (see Fig. 2).

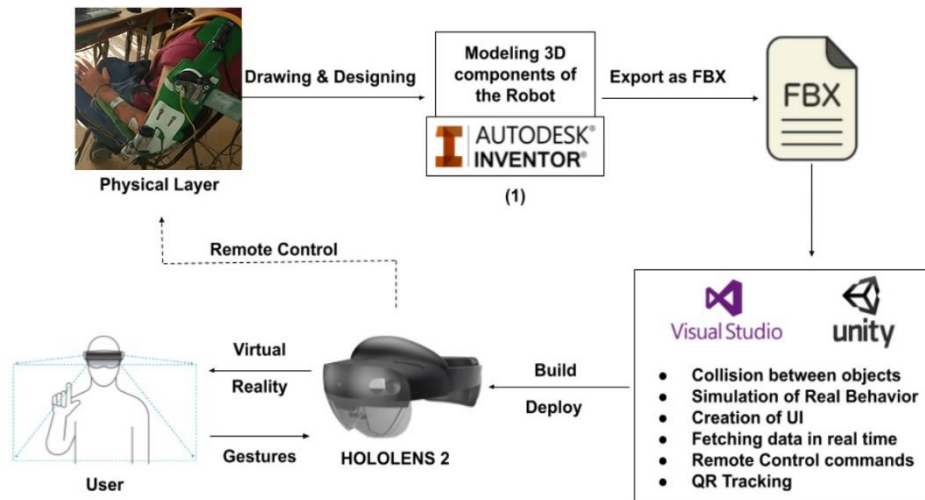


Fig. 2 – Integration of the Exoskeleton with HoloLens 2 Using Unity and Autodesk Inventor.

Several key features were implemented during this development phase:

- **Collision detection and simulation:** Preventing the occurrence of unsafe or anatomically incorrect movements by modeling realistic physical interactions between exoskeleton segments;
- **Augmented reality user interface (UI):** Incorporating gesture-driven menus, virtual control panels, and dynamic status indicators tailored for immersive interaction;
- **Real-time wireless communication:** Using WiFi or Bluetooth to enable data exchange between the Unity application and the exoskeleton's microcontroller, including control signals and sensor feedback.
- **Gesture and voice command integration:** Leveraging the official HoloLens 2 SDK and the **Mixed Reality Toolkit (MRTK)** to allow natural, hands-free interaction with the system.

This phase represents one of the most critical and technically demanding steps in the system's development. It marks the transformation of a digital prototype into a *clinically viable, immersive rehabilitation tool*, ready for deployment in real-world therapeutic scenarios.

4. Unity Integration of the EXOSLIM System

The digital representation of the holonomic EXOSLIM system was integrated into the Unity ecosystem by importing its components from a CAD model in *.FBX* format.

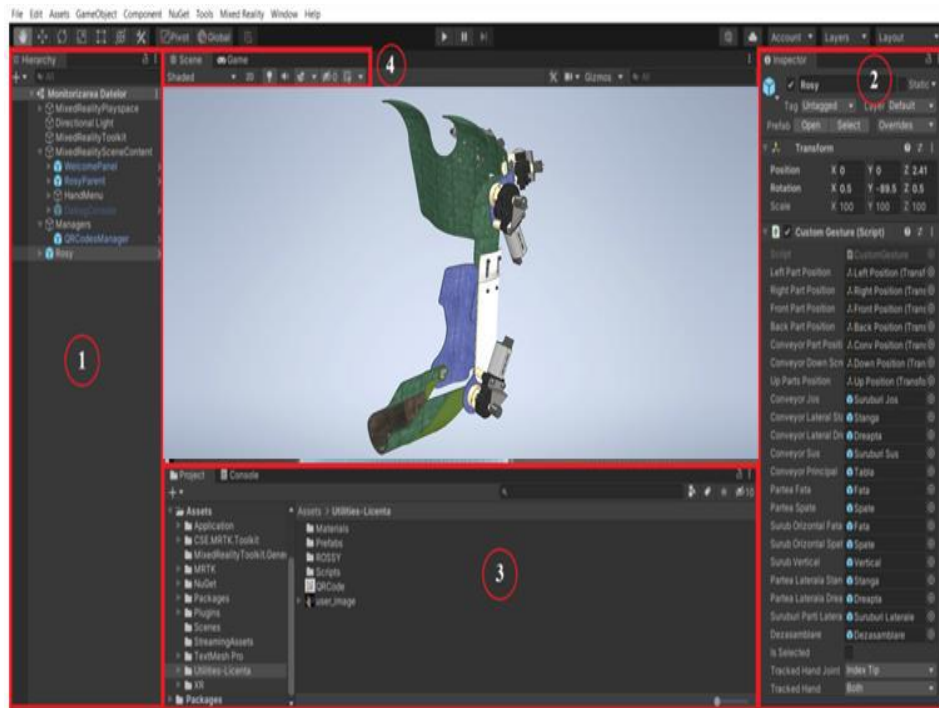


Fig. 3 – Integration in Unity – Main Window.

The CAD model was converted into a collection of polygons and materials, referred to as *GameObjects* within Unity. After constructing these *GameObjects*, the DT-type robotic hand is ready for calibration to replicate the real-world behavior of the physical system (see Fig. 3).

Moreover, these *GameObjects* possess several editable attributes—such as orientation, position, material properties, animations, or scale—that can be modified during this process. Additionally, they can have associated C# scripts capable of animating the DT-type exoskeleton.

5. Adaptive Feedback with HoloLens 2 in Augmented Reality

Through **hand gesture recognition**, the system detects movements such as stretching, grasping, lifting, or touching, triggering real-time visual and auditory responses (Ungureanu, 2020).

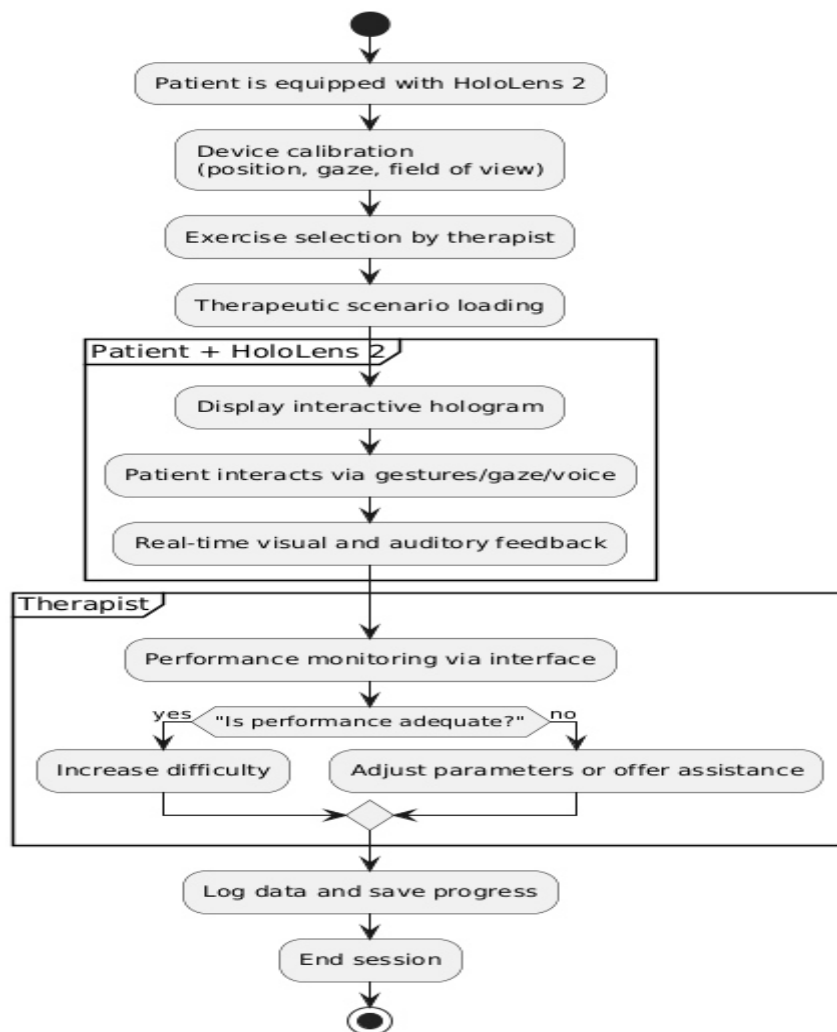


Fig. 4 – The Logical Flow of a HoloLens 2.

For example, if the patient extends their arm to reach a hologram, it may change color, emit a confirmation sound, or display a success score. In cases where the movement is incomplete or incorrect, the system can provide corrective feedback in the form of a guided trajectory or visual warning signals.

As such, the feedback provided by HoloLens 2 is adaptive and personalized, being automatically adjusted based on the user's behavior.

Additionally, the system can integrate virtual mirror exercises, in which the healthy side of the body is reflected onto the affected side, creating the illusion that both limbs move in sync (see Fig. 4). This technique is particularly valuable in the treatment of hemiparesis, as it stimulates the motor cortex of the affected hemisphere through indirect visual activation. The user can observe a virtual reproduction of their own movement, which enhances motivation and facilitates the reconnection of neural circuits involved in motor control.

Throughout the session, the therapist monitors the process through a separate control interface, either on a laptop or a tablet. The therapist can modify the type of exercises, increase or decrease the difficulty level, and visualize data generated by the system regarding reaction time, movement accuracy, number of errors, or perceived effort. In this way, rehabilitation becomes not only an active process but also a measurable and adaptable one in real time, without the need for bulky equipment or invasive interventions.

6. Wireless Communication Architecture between HoloLens 2 and ESP32 from EXOSLIM

To ensure communication between the MR interface (HoloLens 2) and the control unit (ESP32), a dedicated wireless network is established. This network operates without an internet connection and is specifically configured to provide a fast, stable, and low-latency communication channel. The ESP32 functions either as a WiFi.

In both cases, the HoloLens 2 connects to the same network and sends HTTP requests to the microcontroller's local IP address. An asynchronous web server is implemented on the ESP32 using the *ESPAsyncWebServer* library.

This library allows efficient handling of multiple simultaneous requests without blocking the main execution thread, a critical requirement in real-time applications such as motor rehabilitation. The server is initialized on port 80, the standard for HTTP communication.

The Unity application running on the HoloLens sends requests such as *GET /open-hand* or *GET /close-hand*, which are mapped on the ESP32 to functions that activate or deactivate digital outputs connected to relays controlling the glove's actuators according to Fig. 5.

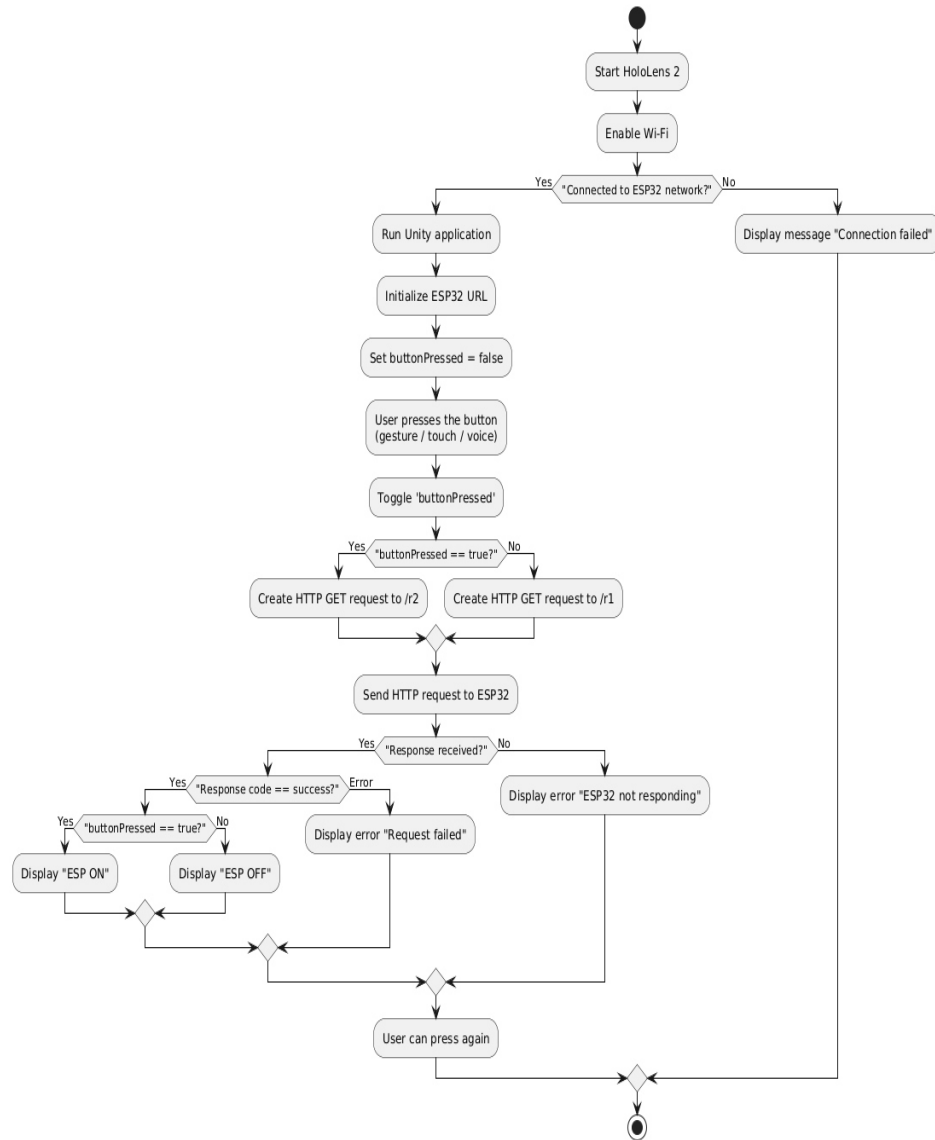


Fig. 5 – HoloLens 2-ESP32 Communication Flow for HTTP Request Handling.

7. Control of Joint θ_1 Using HoloLens 2 and PID Regulation

In the context of robot-assisted rehabilitation or the control of mechatronic systems with multiple degrees of freedom, intuitive human – machine interaction plays a crucial role. The mixed reality technology offered by HoloLens 2 enables direct, intuitive, and real-time control of a robotic system,

eliminating the need for traditional physical interfaces (see Fig. 6). This section specifically describes the control mechanism for the angle θ_1 , associated with the first rotary joint of a serial robotic arm, using the gesture and voice interface of the HoloLens 2 device, along with the registered force level.

The analyzed robotic arm consists of three segments connected by rotary joints, each defined by a rotation angle in its own plane: θ_1 , θ_2 , and θ_3 . Specifically, the angle θ_1 defines the rotation of the first segment around the Z_1 axis and is responsible for the initial motion of the entire assembly relative to the robot's fixed base (reference frame $\{X_0, Y_0, Z_0\}$).

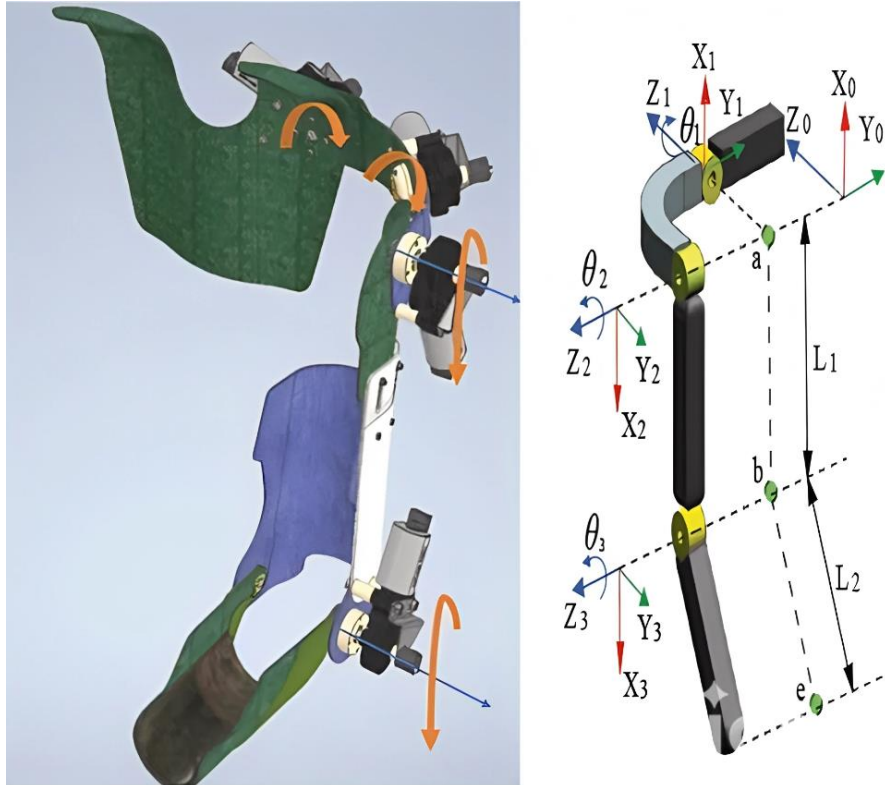


Fig. 6 – Joint Trajectory Control and Simulation of an Upper Limb Assistive Exoskeleton.

This angle holds particular importance, as its variations directly influence the global positioning of the entire kinematic chain. For controlling the angle θ_1 , an integrated system was used, composed of **HoloLens 2**, the **Unity 3D** platform, and the **Mixed Reality Toolkit (MRTK)** package.

The interface created in the virtual environment includes a 3D slider

positioned within the user's field of view, as well as a visual feedback mechanism displaying the current angle value.

The user can modify the value of θ_1 either by:

- directly interacting with the virtual slider using “*grab and drag*” gestures,
- or by issuing voice commands, such as “*Set angle to 45 degrees*”.

This approach enables a hands-free control mechanism, which is essential in clinical or experimental scenarios where the user must simultaneously interact with other equipment or patients. Once the desired value for angle θ_1 is selected, it is transmitted from the HoloLens 2 to a microcontroller (e.g., ESP32) via a Wi-Fi connection, in the form of a JSON packet (e.g., $\{"theta1": 45\}$). The microcontroller interprets the command and generates a control signal (PWM or serial) for the electric motor associated with the respective joint. For improved accuracy and reliability, the system may include position feedback obtained from a rotary encoder mounted on the θ_1 joint axis. The current angle value is returned to the HoloLens interface and displayed in real time, enabling fine-tuned motion adjustment. To ensure precise tracking and minimal steady-state error in the movement of joint θ_1 a classical PID (Proportional – Integral – Derivative) control strategy is employed. The PID controller continuously compares the desired angle θ_1^{ref} (received from HoloLens 2) with the actual measured angle θ_1^{meas} from the encoder, computing the control error:

$$e(t) = \theta_1^{\text{ref}}(t) - \theta_1^{\text{meas}} \quad (1)$$

The control signal $u(t)$ sent to the motor is calculated as follow:

$$u(t) = K_p \times e(t) + k_I \int_0^t e(\tau) d\tau + K_D \frac{de(t)}{dt} \quad (2)$$

where:

- K_p is the proportional gain (affecting response speed),
- K_i is the integral gain (eliminating steady-state error),
- K_D is the derivative gain (anticipating error trends).

The resulting signal $u(t)$ is used to adjust the motor's position via PWM control or through a motor driver interface, ensuring that the actual angle θ_1 follows the desired reference with high fidelity. This real-time feedback loop allows the system to correct deviations dynamically and adapt to external disturbances or joint friction.

Once the PID parameters (K_p , K_i , K_D) have been tuned either

empirically or through methods like Ziegler – Nichols, the control system can generate the control signal $u(t)$. This signal dynamically regulates the motor position via PWM or a motor driver interface, ensuring the joint angle θ_1 follows the reference signal with minimal error. The real-time feedback loop monitors deviations and responds immediately, compensating for external disturbances, inertia, or joint friction.

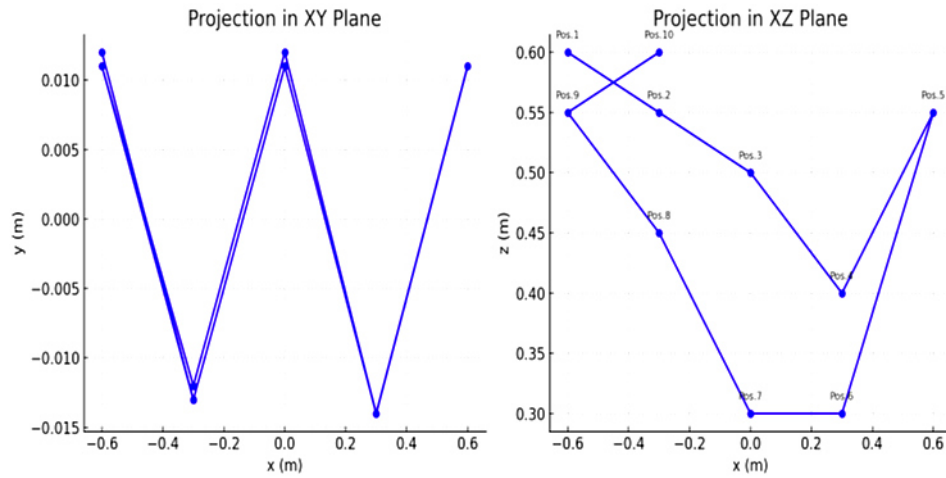


Fig. 7 – Planar Projections of End-Effector Motion (XY and XZ Views).

With the system operating under closed-loop control, EXOSLIM effectively coordinates all four degrees of freedom, allowing the end-effector to follow a predefined path in 3D space.

The trajectory is generated by interpolating target positions, forming a continuous motion profile suitable for rehabilitation tasks. To validate the motion execution, the actual end-effector positions were recorded over time and visualized. The results are shown in Fig. 7 and Fig. 8.

As illustrated in Fig. 7, the **XY projection** (left) demonstrates consistent lateral movement with high symmetry, while the **XZ projection** (right) captures the vertical displacement throughout the motion, showcasing the effective spatial coverage of the workspace. Labeled reference points (“Pos.1” to “Pos.10”) indicate key locations used in the evaluation of the system’s accuracy and repeatability. Furthermore, Fig. 8 presents the complete **3D trajectory**, offering a spatial perspective that confirms the controller’s ability to replicate complex paths with high precision. This level of accuracy, on the order of millimeters, is critical for therapeutic applications where smooth, repeatable, and safe movement is essential.

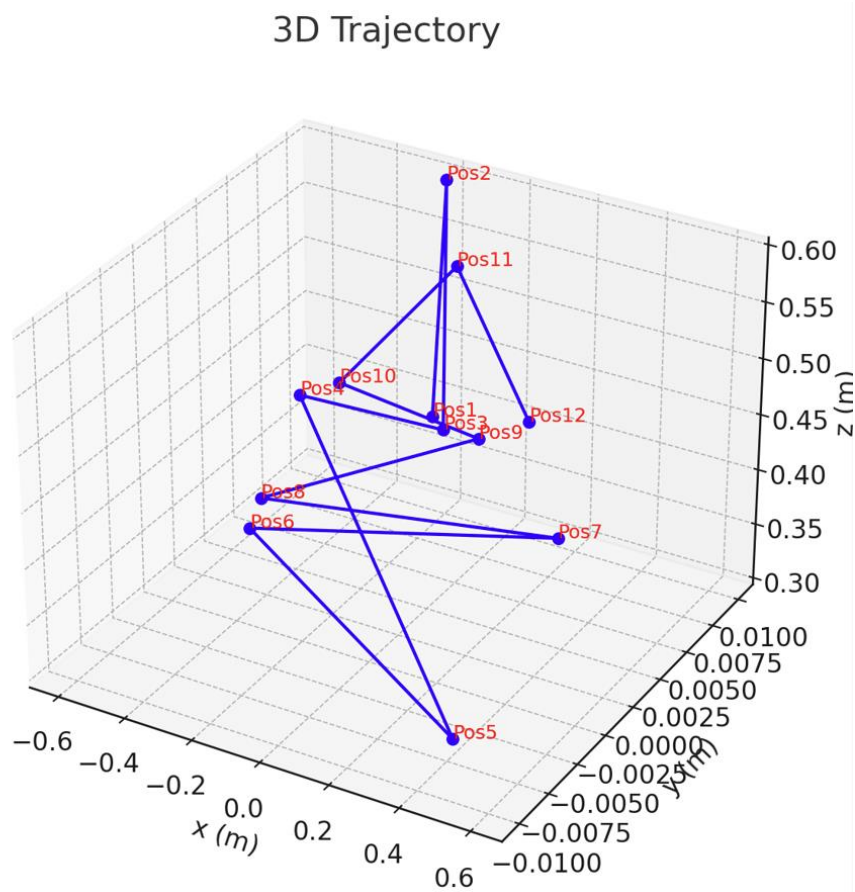


Fig. 8 – Trajectory followed by the end-effector of the EXOSLIM system with 4 DoF.

8. Advantages of VR Control over Joint θ_1

The integration of joint θ_1 control via HoloLens 2 offers the following advantages:

- Intuitive interaction based on natural gestures and voice commands;
- Real-time visual feedback integrated directly into the user's field of view;
- Elimination of traditional physical interfaces (joystick, keyboard, touchscreen);
- Enhanced ergonomics and immersion in robotic system control;
- Scalability, with the potential to extend control to other joints (θ_2 , θ_3 , etc.).

These advantages make this type of control particularly useful in neurological rehabilitation applications, where the therapist can adjust system parameters without breaking contact with the patient.

Table 1
Advantages of Mixed Reality Interfaces in Motor Rehabilitation

Advantage	Description
Intuitiveness	Gesture- and voice-based control, requiring no advanced training.
No physical contact	Ideal for clinical contexts (e.g., post-stroke rehab).
Full mobility	No cables required, the system operates wirelessly.
Real-time feedback	Visual output displayed directly in the user's field of view.
Scalability	The system can be extended to control all robotic joints.

In industrial or educational contexts, the use of mixed reality for robotic joint control can facilitate training and prototype testing without safety risks. The intuitive control of robotic systems with multiple degrees of freedom (DoF) remains a significant challenge in fields such as neurological rehabilitation, advanced mechatronics, and human – robot interfaces.

Mixed reality (MR), enabled through devices like HoloLens 2, provides an innovative solution that enables contact-free interaction by combining natural gestures, voice commands, and real-time visual feedback. This work presents a complete control architecture for a serial robotic arm with three rotary joints, each defined by an angle ($\theta_1, \theta_2, \theta_3$), controlled through the HoloLens 2 interface.

Position feedback is ensured by resistive encoders mounted on each joint, allowing for precise corrections and real-time visualization of the arm's position in both the physical and virtual space.

9. Conclusion

The integration of HoloLens 2 and mixed reality technologies into the control architecture of a serial robotic arm introduces a new paradigm in human – machine interaction. By enabling hands-free operation through natural gestures and voice commands, and by offering real-time visual feedback directly in the user's field of view, this system significantly improves usability, safety, and immersion in both clinical and technical contexts (see Fig. 9).

The proposed solution demonstrates that intuitive, non-invasive control of multiple degrees of freedom can be achieved with high precision, particularly when enhanced by position feedback from resistive encoders. This approach is not only scalable to more complex robotic systems, but also adaptable to various fields, from neurorehabilitation and assistive robotics to industrial prototyping and education.



Fig. 9 – Development tests in laboratory environment.

Mixed reality offers a unique opportunity to bridge the gap between virtual simulation and physical actuation, making robotic control more accessible, responsive, and human-centered than ever before.

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EXOSCHELET PENTRU MEMBRE SUPERIOARE BAZAT PE REALITATE VIRTUALĂ DESTINAT REABILITĂRII NEUROMOTORII

(Rezumat)

Această lucrare prezintă un sistem inovator de reabilitare a membrelor superioare destinat pacienților care au suferit un accident vascular cerebral, combinând un exoschelet personalizat cu o platformă integrată de realitate augmentată (AR). Prin valorificarea tehnologiilor avansate, precum recunoașterea gesturilor și instrumentele AR (de exemplu, Microsoft HoloLens), sistemul urmărește să îmbunătățească recuperarea funcțională și implicarea utilizatorului.

Un prototip de exoschelet proiectat la comandă a fost dezvoltat și testat, punând accent pe controlul precis al traiectoriei articulațiilor, acuratețea cinematică și adaptabilitatea la nevoile individuale ale utilizatorului.

Validarea a fost realizată prin teste de laborator și experimente cu utilizatori (human-in-the-loop), concentrându-se pe performanța controlului, designul ergonomic și siguranță. Mai mult, dezvoltarea și testarea sistemului de exoschelet asistat de AR s-au desfășurat cu implicarea continuă a unui kinetoterapeut, asigurând integrarea expertizei clinice încă din faza conceptuală.

Aceste rezultate susțin integrarea viitoare în protocoale personalizate de reabilitare, pentru obținerea unor rezultate neurofuncționale mai bune, confirmând viabilitatea și potențialul clinic al sistemelor inteligente de exoschelet adaptative la utilizator.