

Myoelectric-Controlled Underactuated Gripper: A Low-Cost EMG-Based Prosthetic Training System

S. Molano, S. Schurz, P. Zahed, and B. R. Bracio

Abstract—This paper presents the development of an underactuated gripper controlled via electromyography (EMG) signals, designed as part of the 'Direct Research Studies' (DRS) module for biomedical engineering master's students. The DRS module provides a structured framework for interdisciplinary research, emphasizing hands-on experience in prototyping, control system integration, and biomedical signal processing. This study highlights the educational benefits of the DRS approach and showcases the collaborative nature of engineering, computer science, and biomedical disciplines in developing assistive technologies.

The gripper was fabricated using additive manufacturing and incorporates an underactuated design to balance cost-effectiveness, and functionality. Real-time EMG signal acquisition and processing were implemented using a BIOPAC MP160 system (BIOPAC Systems Inc., Goleta, CA, USA) and MATLAB R2024a (The MathWorks, Inc., Natick, MA, USA), enabling intuitive binary control of the gripper's actuation.

To complement the physical prototype, a Virtual Reality (VR) environment was developed using Unity 2023.1.10f1 (Unity Technologies, San Francisco, CA, USA) to simulate the gripper's functionality and serve as both a demonstration and training tool. This paper outlines the methodologies, and technical procedures involved in developing the prototype, showcasing how project-based research within an educational framework fosters collaboration and innovation in assistive device design.

I. INTRODUCTION

Advancements in prosthetics and rehabilitation technologies have significantly improved the quality of life for individuals with limb loss. Recent developments in robotics have focused on integrating robotic systems into human environments, particularly in the design and functionality of prosthetic limbs. These efforts aim to enhance functionality while reducing costs, thereby increasing the accessibility of prosthetics to a broader population [1]. Prosthetic limbs can be powered in multiple ways: body-powered systems rely on physical movements and cables (e.g., cables for mechanical actuation), while externally powered systems use electric motors controlled by electrical signals, such as electromyography (EMG), derived from the user's muscles [2].

Externally powered prosthetic systems, such as myoelectric prosthetics, represent a significant advancement in replicating natural limb functionality. By leveraging EMG signals

to drive electric motors, these systems provide precise, user-controlled movement, enabling complex tasks such as gripping and releasing objects. However, challenges remain in optimizing these systems for greater affordability, robustness, and ease of use. Emerging technologies, including 3D printing, myoelectric control advancements, and virtual reality (VR), hold great promise for addressing these challenges while further enhancing the design, functionality, and accessibility of prosthetic devices [1].

This paper presents a project conducted as part of the "Direct Research Studies" (DRS) module for master's students in biomedical engineering at the Anhalt University of Applied Sciences, Germany, providing participants with hands-on experience in research, development, and prototyping. The primary objective of this project was to design and implement a 3D-printed prosthetic gripper controlled by EMG signals, serving as a prototype for upper-limb prosthetics. Furthermore, a VR-based training environment was developed to facilitate user adaptation and proficiency with the prosthetic system.

This interdisciplinary project emphasized the development of practical skills, including designing and 3D-printing a functional gripping mechanism, processing EMG signals for myoelectric control, and programming a VR environment for user training. Conducted over a 15-week period as part of the DRS module, the project enabled participants to develop and apply modern biomedical techniques within a structured, research-oriented framework. Although clinical validation and performance testing were beyond the scope of this project, the results highlight the feasibility and potential of integrating 3D printing, EMG signal processing, and VR technologies in modern prosthetic design.

II. METHODS

In the initial phase of the project, three interfacing tasks were defined based on the desired learning outcomes of the participating students:

- 1) 3D Printing – Design and fabricate a robotic gripper.
- 2) Data Acquisition and Control – Acquire and process an electromyographic (EMG) signal.
- 3) Programming of VR Environments – Develop a VR-based training environment.

The following sections will discuss these tasks in detail.

A. Design and Fabrication of the Gripper

The task was to design a gripper actuated by an external force and controlled by myoelectric EMG signals captured from the human body. To align with the learning objectives

S. Molano, S. Schurz, and P. Zahed are with the Department of Biomedical Engineering, Anhalt University of Applied Sciences, Köthen, Germany (emails: juanesebastian.molanocortes@student.hs-anhalt.de, sylvana.schurz@student.hs-anhalt.de, pezhman.zahed@student.hs-anhalt.de)

Prof. Dr. B. R. Bracio, also with the Department of Biomedical Engineering, Anhalt University of Applied Sciences, Köthen, Germany (email: bracio@ieee.org).

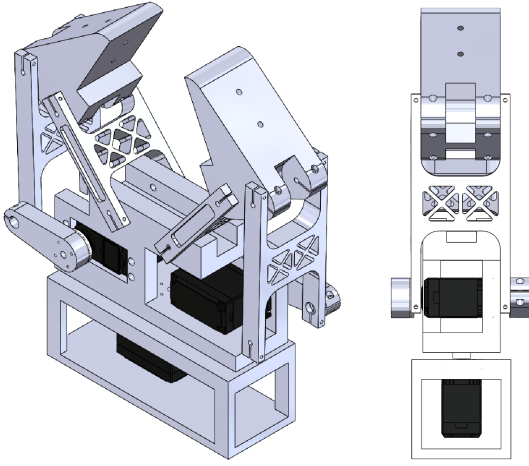


Fig. 1. CAD Model of the Underactuated Gripper Created in SolidWorks

of the project, 3D printing was chosen as the manufacturing method, leading to the identification of the following sub-tasks:

- Review state of the art 3D-printed prostheses.
- Identify and select viable designs.
- Develop a parametric CAD model.
- Convert CAD models into G-code for fabrication.
- Fabricate and assemble the gripper.

Underactuated grippers have been recognized as effective solutions for various applications due to their ability to achieve stable and adaptive grasping with fewer actuators than degrees of freedom [3]. This design reduces cost, simplifies control, and lowers overall weight while maintaining effective object handling [4].

Building on these advantages, the gripper was designed in SolidWorks 2022 (Dassault Systèmes, Vélizy-Villacoublay, France), with a five-bar linkage mechanism based on an existing reference model [5]. This mechanism, passively actuated by a spring, was adapted to enable controlled grasping of objects with varying shapes and sizes. The spring enables adaptation of the gripper, allowing single-motor actuation and reducing system complexity, as shown in Fig. 1.

Each component of the gripper was individually modeled and assembled into a complete virtual model using SolidWorks 2022. The finalized CAD models were then translated into machine-readable instructions using Ultimaker Cura 5.7.1 (Ultimaker, Geldermalsen, Netherlands), which generated the corresponding G-code files required for additive manufacturing. These G-code files, containing precise toolpath commands for layer-by-layer material deposition, were subsequently executed by an Ultimaker 3 (Ultimaker, Geldermalsen, Netherlands) 3D printer to fabricate the physical components.

The gripper components were 3D-printed using PLA filament (3.00 mm) with a 0.4 mm nozzle and a layer height of 0.2 mm. Printing was performed at 210°C with a speed of 60–70 mm/s and a triangular infill pattern at 20–25% density to balance strength and material efficiency.

The assembled gripper is actuated by three metal gear servo motors, MG-996R (Owootec, Shenzhen, China), each with a stall torque of 9.4–11 kg-cm and an operating voltage of 4.8–6.6 V. Metal gear servos were chosen to enhance durability and reduce wear compared to plastic alternatives, making them more suitable for applications involving repeated actuation. One servo motor controls rotation, while the other two operate the gripping mechanism to facilitate object grasping.

The design and fabrication process integrated parametric modeling, additive manufacturing, and component assembly to develop a functional underactuated gripper. The selected materials and actuation system were chosen to achieve a balance between mechanical simplicity and adaptability. With the physical prototype completed, as shown in Fig. 2, the next phase focuses on implementing EMG-based control to facilitate user-driven actuation.

B. EMG Signal Acquisition and Processing

This section outlines the methodology for EMG data acquisition and processing, including electrode placement, signal preprocessing, feature extraction, and experimental procedures. It also covers the implementation of a finite state machine (FSM) for real-time classification and a MATLAB-based environment for simulating and validating gripper movements.

1) Evaluation and Selection of available EMG Acquisition Systems: Two EMG acquisition platforms were evaluated: the MyoWare Muscle Sensor (Advancer Technologies, Raleigh, NC, USA) and the MP160 Data Acquisition System (BIOPAC Systems Inc., Goleta, CA, USA). Assessment criteria included signal fidelity, sampling frequency, noise susceptibility, integration ease, and real-time acquisition capabilities. A summary of these specifications is provided in Table I.

While the MyoWare sensor offers a compact and cost-effective solution, its lower signal-to-noise ratio and susceptibility to motion artifacts limit its suitability for precise control. In contrast, the MP160 system provided superior signal quality, higher sampling rates, and enhanced noise resistance. Integration with the BIOPAC BIONOMADIX

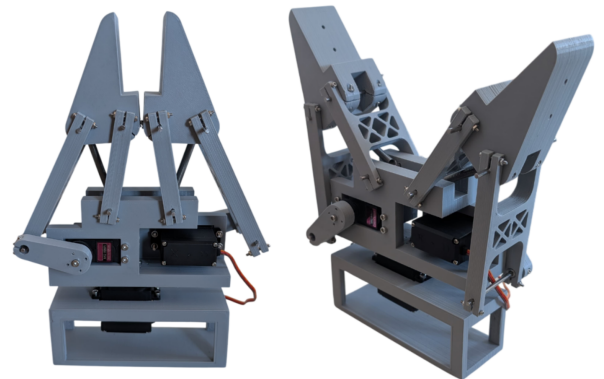


Fig. 2. Final Assembly of the 3D-Printed Underactuated Gripper

TABLE I
COMPARISON OF MYOWARE AND MP160 EMG ACQUISITION SYSTEMS

Specifications	EMG Acquisition System	
	MyoWare	MP160
Signal Quality	SNR: 20–30 dB	SNR: 60–70 dB
ADC Resolution	10-bit (limited by Arduino)	24-bit (high precision)
Channels	Single-channel	Multi-channel
Sampling Rate	Up to ~ 1 kHz	Up to 200 kHz
Bandwidth	Not specified	10–500 Hz (BIONOMADIX)
Common-Mode Rejection Ratio (CMRR)	Not specified	> 110 dB (BIONOMADIX)
Weight	Sensor: ~ 5 g; Arduino: ~ 25 g	BIONOMADIX: ~ 54 g
Software	Arduino IDE	BIOPAC API, MATLAB, AcqKnowledge
Real-time Data Acquisition	Limited (depends on Arduino)	Yes, low-latency
Wireless Capability	No	Yes (BIONOMADIX Wireless)
Cost	Low (\$40–\$70)	High (\$5,000)
Connectivity	Compatible with Arduino and microcontrollers	Integrates with BIOPAC modules
Regulatory Compliance	Not specified	Research-grade certification

amplifier further improved mobility and real-time acquisition. Due to these advantages, the MP160 system was selected for this project.

2) *BIOPAC Data Acquisition Methods:* Data acquisition from the MP160 system can be achieved through network-based methods like TCP or UDP sockets, which require expertise in network programming and additional setup. Alternatively, the BIOPAC Hardware API provides a more efficient solution via a Dynamic Link Library (DLL) interface, compatible with C, C++, Python, MATLAB, and LabVIEW. This approach eliminates the need for intermediate network

protocols, ensuring low-latency, high-speed data transfer. Due to its efficiency and simplicity, the BIOPAC Hardware API was selected for this study.

3) *Electrode Placement and Lead Configuration:* The EMG2-R module supports up to six leads for EMG signal acquisition. Electrodes were placed on the biceps brachii and anterior deltoid to ensure accurate signal capture. For the biceps brachii, 30 mm electrodes were positioned at one-third the distance between the acromion and lateral epicondyle, with a 50 mm inter-electrode distance (Fig. 3). Anterior deltoid electrodes were placed 15 mm lateral to the clavicle, maintaining a 50 mm inter-electrode distance. A reference electrode was placed on the user's fingertips, as this configuration demonstrated superior signal stability and quality.

4) *EMG Data Collection Protocol:* Sample data recordings consisted of a two-minute EMG session, during which muscle activation patterns were captured at a sampling rate of 200 Hz while performing predefined tasks. The protocol included baseline recording, controlled contractions, and task repetitions to ensure reliability and minimize variability.

For artifact rejection and signal normalization, the subject remained at rest for the first and last 24 seconds, establishing a baseline noise profile. Subsequently, three tasks targeting the biceps brachii and anterior deltoid were performed, maintaining a 1:1 contraction-relaxation ratio. An auditory metronome in MATLAB ensured a consistent tempo of 0.5 Hz (2 s per cycle) to standardize muscle activation timing. These tasks included:

- **Biceps Activation:** The subject performed ten hand closures at 40% of maximum voluntary contraction (MVC) to activate the biceps brachii while minimizing co-contraction.
- **Anterior Deltoid Activation:** The subject performed six

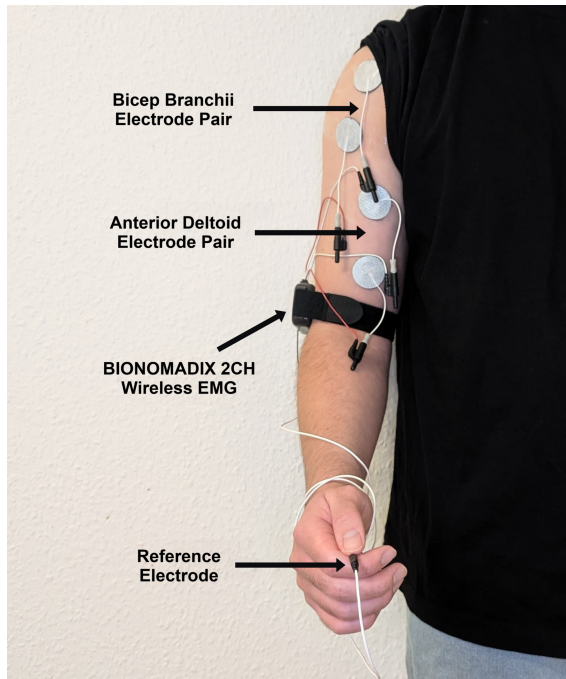


Fig. 3. Electrode Lead Placement Configuration

frontal arm lifts through a controlled 90° range in the sagittal plane to activate the anterior deltoid while minimizing biceps engagement.

- **Frontal Arm Hold with Biceps Contraction:** The subject maintained the arm at 90° relative to the torso, alternating between 3-s biceps contractions and relaxations for six cycles. This task assessed sustained activation and EMG signal stability.

Throughout the session, real-time signal visualization and quality checks were conducted to detect signal saturation, motion artifacts, and electrode displacement, ensuring consistent EMG acquisition. The acquired data is presented in Fig. 4.

5) *Data Filtering and Preprocessing:* The raw EMG sample signals, consisting of 40,000 data points (20,000 per channel), underwent a series of preprocessing steps to enhance signal quality and facilitate downstream analysis.

a) *Interleaved Data Separation and Rectification:* Initial preprocessing involved separating interleaved data from the two channels by extracting alternate samples. Rectification was then applied to ensure non-negative data:

$$x_{\text{rect}}(n) = |x(n)| \quad (1)$$

where $x(n)$ represents the raw EMG signal at sample n .

b) *Thresholding for Channel 1:* Channel 1 exhibited a constant noise floor of approximately 1.2 Volts, even in the absence of muscle activation. To mitigate this, a thresholding operation was applied:

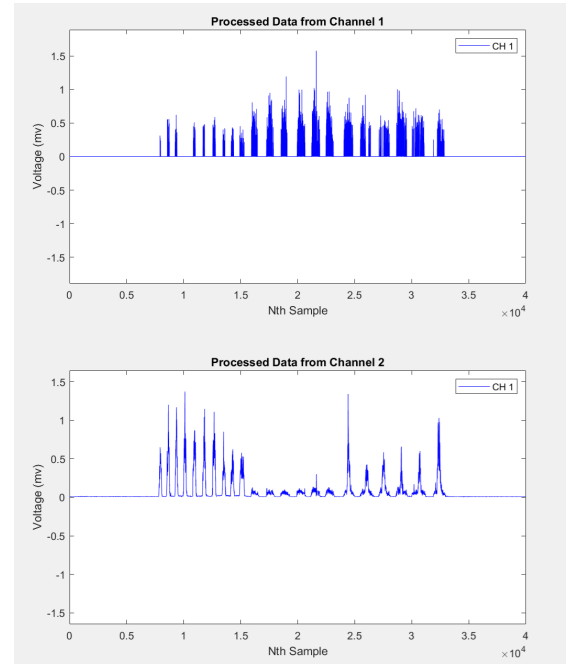


Fig. 5. Processed EMG Signals

$$x_{\text{th}}(n) = \begin{cases} x_{\text{rect}}(n) - 1.2, & \text{if } x_{\text{rect}}(n) > 1.2 \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

This ensures that only meaningful activations contribute to further processing while eliminating background noise.

c) *Noise Reduction:* A median filter and a moving average filter with a window size of nine were applied to smooth short-term fluctuations while preserving the overall signal trend.

The median filter is defined as:

$$y(n) = \text{median}\{x_{\text{th}}(n-k), \dots, x_{\text{th}}(n), \dots, x_{\text{th}}(n+k)\} \quad (3)$$

where $k = 4$, resulting in a total window size of $2k + 1 = 9$ samples.

The moving average filter is expressed as:

$$y(n) = \frac{1}{N} \sum_{i=0}^{N-1} x_{\text{th}}(n-i) \quad (4)$$

where $N = 9$ represents the window size.

d) *Butterworth Bandpass Filtering:* A fourth-order Butterworth bandpass filter was implemented to retain muscle activity within the 10–90 Hz range while attenuating motion artifacts and high-frequency noise.

The transfer function of an N -order Butterworth filter is:

$$H(s) = \frac{1}{\sqrt{1 + \left(\frac{s}{\omega_c}\right)^{2N}}} \quad (5)$$

where ω_c is the cutoff frequency and $N = 4$.

A bandpass filter was realized by cascading a high-pass and a low-pass Butterworth filter:

$$H_{\text{bp}}(s) = H_{\text{hp}}(s)H_{\text{lp}}(s) \quad (6)$$

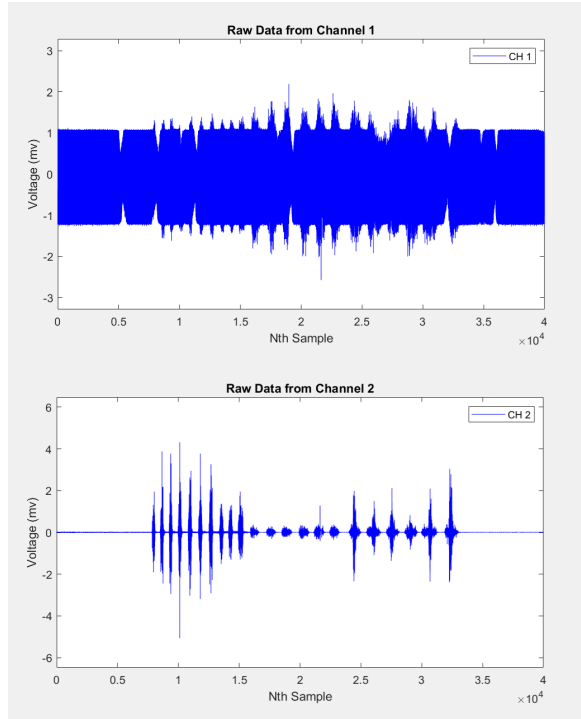


Fig. 4. Sample raw EMG signals recorded from two channels using the MP160 system with the BIOPAC BioNomadix 2CH Wireless EMG module.

where $H_{hp}(s)$ and $H_{lp}(s)$ are the high-pass and low-pass filter transfer functions, respectively.

e) *Zero-Phase Filtering*: To prevent phase distortion, zero-phase filtering was applied using the forward-backward method:

$$y_{\text{filt}}(n) = \text{filtfilt}(b, a, x_{\text{th}}(n)) \quad (7)$$

where b and a are the filter coefficients obtained from the Butterworth design.

The results of these filtering processes, designed to enhance feature extraction for Control Command Generation, are shown in Fig. 5.

6) *Control Command Generation*: To convert the pre-processed EMG signals into control commands, a binary activation algorithm was developed. This algorithm classified each sample as active or inactive based on a predefined amplitude threshold of 0.5 mV, as shown in Fig. 7.

A finite state machine (FSM) was implemented to interpret these binary signals and generate control commands corresponding to specific movement intentions (Fig. 6). The FSM was designed to produce one of four distinct control states: up, down, forward, and backward.

7) *MATLAB-Based Visualization Environment*: A simulation environment was developed to visualize generated control commands and corresponding gripper motion. To achieve this, STL files of the gripper were processed to extract geometric and topological data. The geometric data defined the spatial coordinates of the model in $\mathbb{R}^3$, while the topological data represented connectivity relationships, forming a triangular mesh using an adjacency matrix. These datasets allowed the application of linear transformations to simulate real-time motion.

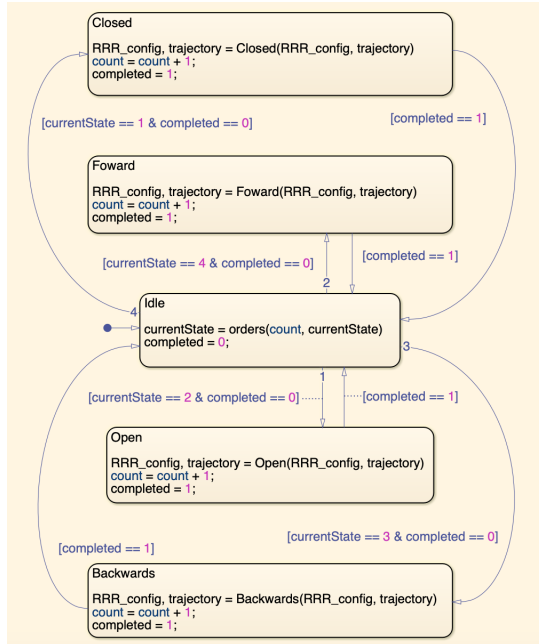


Fig. 6. Finite State Machine Implementation in MATLAB Simulink

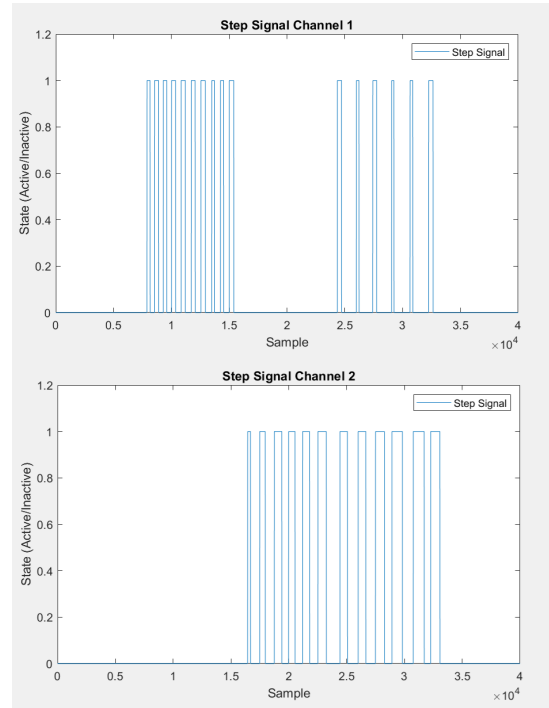


Fig. 7. Binary Control Signals for Command Execution

To model gripper movement, a homogeneous transformation matrix was used:

$$\mathbf{T} = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ 0 & 1 \end{bmatrix} \quad (8)$$

where:

- $\mathbf{R} \in SO(3)$ is the rotation matrix representing angular transformations.
- $\mathbf{t} \in \mathbb{R}^3$ is the translation vector.

Each gripper component was assigned an individual transformation matrix, allowing independent motion control. The position update for any point $\mathbf{p}_i$ in homogeneous coordinates was computed as:

$$\mathbf{p}'_i = \mathbf{T}\mathbf{p}_i = \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix} \quad (9)$$

To ensure smooth transitions between control states, linear interpolation (LERP) was applied:

$$\mathbf{P}(t) = (1 - \alpha)\mathbf{P}_0 + \alpha\mathbf{P}_f, \quad \alpha \in [0, 1] \quad (10)$$

where:

- $\mathbf{P}_0$ and $\mathbf{P}_f$ are the initial and final positions.
- α is dynamically adjusted to provide continuous motion.

This framework enabled real-time visualization of the prosthetic gripper's movements based on EMG input, validating its functionality before integration into a VR environment. The results of this operations can be seen in Fig. 8 and Fig. 9.

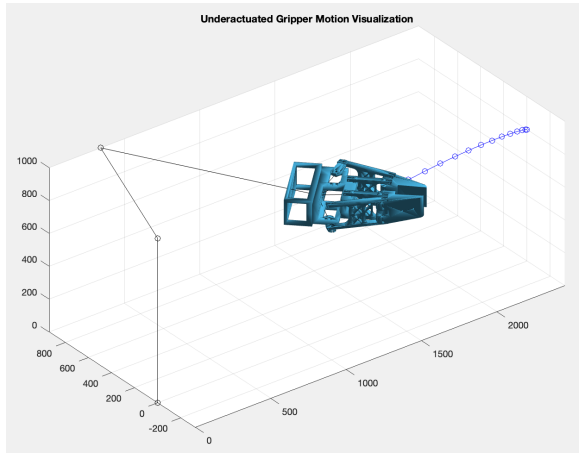


Fig. 8. MATLAB-Based 3D Visualization of Underactuated Gripper Motion

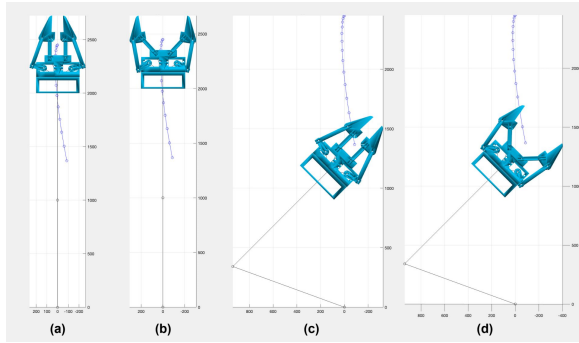


Fig. 9. The figure illustrates the four primary motion states of the underactuated gripper as visualized in the MATLAB simulation environment. These states include: (a) extended and closed, (b) extended and open, (c) retracted and closed, and (d) retracted and open.

C. VR Environment Development

1) *Introduction and Motivation for VR:* Virtual Reality (VR) is a powerful tool in rehabilitation, providing an immersive, controlled environment for motor skill practice while enabling precise patient assessment [9]. VR-based therapy enhances motivation, adherence, and cost-effectiveness compared to traditional methods, contributing to physiological, psychological, and functional recovery [10]. Additionally, it offers systematic progress tracking, minimizing human errors in assessment [9].

A major challenge in upper-limb rehabilitation is the difficulty amputees face in mastering prosthetic control, often leading to device abandonment due to fatigue, low motivation, and complexity. This underscores the need for an engaging and low-risk training environment.

To address the challenges in upper-limb rehabilitation, a simulated game environment was developed using Unity 6 (Unity Technologies, San Francisco, CA, USA). Unity 6 was selected for its broad platform support, XR Interaction Toolkit, user-friendly interface, C# scripting capabilities, and customizable VR interactions.

To evaluate system effectiveness, existing research on VR-based rehabilitation was examined, identifying two well-

established games. These games were recreated in Unity, adhering to documented dimensions and mechanics to ensure clinical relevance and rehabilitation efficacy [6], [7].

2) *Utilizing BBT and Shelf Sorting for VR-Based Motor Rehabilitation:* To enhance upper-limb rehabilitation in a virtual environment, two established assessment tasks were implemented:

The Box and Blocks Test (BBT), a widely recognized test for hand functionality, was developed using Unity 2023.1.10f1 (Unity Technologies, San Francisco, CA, USA) and C# and integrated into an Oculus Rift (Meta Platforms, Menlo Park, CA, USA) VR system [6]. This task, where users transfer cubes between compartments (Fig. 10), serves as a key measure of prosthetic control, particularly for upper-limb amputees. Its design follows the standardized dimensions established in [8].

The shelf-sorting game (Fig. 11) engages users in upper-extremity rehabilitation by categorizing colored cubes on different shelf levels, promoting essential motor exercises such as grasping, releasing, and controlled arm movements. Both tasks provide an immersive and structured approach to fine and gross motor rehabilitation.

3) *Challenges in Designing and Implementing a VR Environment:* Developing the VR environment in Unity required precise integration of complex 3D objects. Since Unity provides only basic geometric primitives, external modeling software was necessary. SolidWorks was chosen

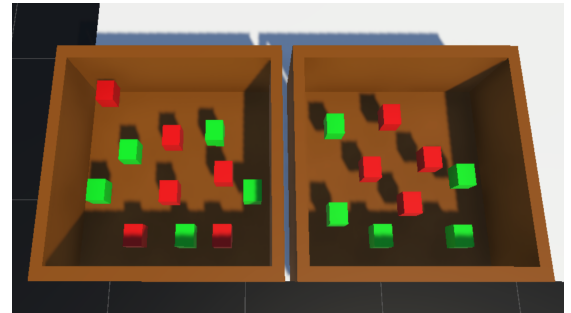


Fig. 10. Virtual Box and Blocks Test (BBT) in a VR environment

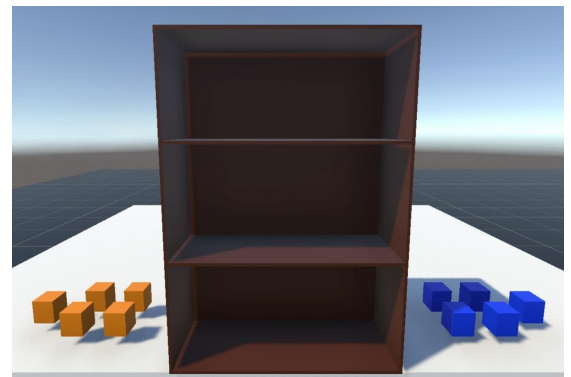


Fig. 11. Shelf sorting implementation in a VR environment for upper-extremity rehabilitation

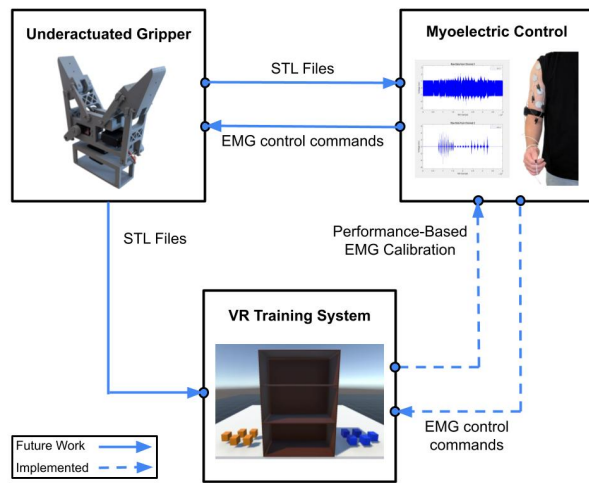


Fig. 12. System Data Flow, Completed Work, and Future Development in EMG-Controlled Prosthetic Training

for its parametric design capabilities, ensuring accuracy in structured object creation.

Since Unity lacks native .STL support, Blender 3.6 (Blender Foundation, Amsterdam, Netherlands) converted files to .FBX for integration. To ensure accurate collisions, convex hull approximations and compound colliders were used, enhancing interaction fidelity and computational efficiency.

III. RESULTS

The implementation of an EMG-controlled underactuated gripper offered students hands-on experience in biomedical signal processing, control systems, and additive manufacturing. Participants successfully acquired and processed EMG signals to operate both a MATLAB-based virtual gripper and a 3D-printed physical gripper, providing a practical understanding of system functionality. Additionally, the introduction of a VR training environment exposed students to interactive simulation and user-centered assistive technology design. While full EMG-VR integration remains an objective for future work, as depicted in Fig. 12, the project effectively met its educational goals by promoting interdisciplinary collaboration and experiential learning in prosthetic development.

IV. DISCUSSION

The successful demonstration of EMG-controlled actuation highlights the feasibility of this approach; however, the incomplete integration of the VR training environment limits its practical applicability. The current binary control system, though operational, restricts movement precision and could be improved through enhanced EMG calibration and machine-learning-based classification. Furthermore, incorporating performance metrics such as response latency and accuracy would strengthen system validation and usability. Future advancements should prioritize real-time synchronization between the VR system and the physical gripper to enhance immersion and training effectiveness.

While this study is primarily educational, its impact on medicine lies in training future biomedical engineers with practical experience in prosthetic development, myoelectric control, and assistive technology design. By fostering interdisciplinary learning, it contributes to the long-term advancement of rehabilitation tools and affordable prosthetic solutions.

V. CONCLUSION

This project successfully established an educational framework for EMG-controlled prosthetic development by integrating signal acquisition, myoelectric actuation, and VR simulation. The ability to control both virtual and physical grippers validated key learning outcomes, though further improvements in EMG processing and VR interaction are necessary to enhance usability. Beyond reinforcing fundamental biomedical engineering concepts, this initiative fostered interdisciplinary collaboration and practical skill development. By bridging multiple technical domains, it supports the training of future engineers and advances accessible prosthetic technologies.

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