Low-Cost Myoelectric Prosthetic Arm

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***Abstract** - The development of low-cost myoelectric prosthetic arms has been a pivotal area of research, aiming to provide functional solutions for individuals with limb loss. This research presents a novel approach to a prosthetic arm controlled via Bluetooth from a mobile application, eliminating the need for traditional EMG sensors. The proposed system integrates an **AVR microcontroller**, **HC-05 Bluetooth module**, and **MG996R servo motors** to provide affordable, efficient, and intuitive control of the prosthetic device. The mobile application serves as a user-friendly interface, where the user can send simple commands (e.g., open and close grip) to control the prosthetic arm's movements. The system is powered by a **7.4V Li-Po battery**, ensuring sufficient operation time for daily tasks. The design employs a **3D-printed prosthetic hand** with articulated fingers and a thumb, which are driven by servo motors for basic hand functions. The absence of EMG sensors reduces both cost and complexity, making the system highly accessible. User trials showed that the prosthetic arm can successfully perform tasks such as grasping and releasing objects, with the added benefit of easy setup and customization. This research demonstrates the potential for Bluetooth-controlled prosthetic systems to offer a cost-effective and accessible solution to individuals with limb loss, especially in resource-constrained settings (Englehart & Hudgins, 2003; Ten Kate et al., 2017; Salmond et al., 2020).*

***Keywords** - Bluetooth-controlled prosthetic, 3D-printed prosthetic, Low-cost prosthetics, Myoelectric prosthetic arm, Servo motor prosthesis.*

1. Introduction

The use of prosthetic limbs has significantly evolved over the last few decades, providing individuals with the ability to regain functionality and independence. Traditionally, prosthetics have ranged from basic mechanical devices to advanced systems with myoelectric sensors that control the movement of the limb based on electrical signals from the user's muscles (Englehart & Hudgins, 2003). While advanced prosthetics offer greater precision and control, the high cost of these systems remains a major barrier to accessibility, particularly in developing countries or for individuals without access to advanced healthcare resources (Ten Kate et al., 2017).

The prosthetic arm proposed in this research leverages Bluetooth communication to enable wireless control from a mobile app, where the user can input simple commands to actuate the hand's movements. Bluetooth is a reliable, widely available technology that can interface with mobile devices, making it an ideal choice for controlling prosthetic limbs, as it allows for real-time, wireless control (Salmond et al., 2020). The system incorporates Microcontroller and servo motors to control the movement of the prosthetic fingers, providing the user with essential functions such as grasping, holding, and releasing objects.

The goal of this project is to design and implement a cost-effective prosthetic arm that can deliver basic, but essential, hand movements through an intuitive mobile interface, without the need for complex sensor-based control systems. In addition to reducing costs, the system's **modular design** and **3D-printed components** allow for easy customization and repair, further increasing its accessibility and lifespan.

The following sections of this paper outline the **background** of prosthetic arm technology, the **proposed methodology** for the design and implementation of the system, its **objectives**, and the results of the testing and performance evaluation. The study aims to demonstrate that such a system can effectively replace traditional myoelectric systems and provide a viable, **affordable prosthetic solution** for a wide range of users.

This research aims to expand the understanding of low-cost prosthetics and contribute to the development of **affordable assistive technologies** that can help improve the quality of life for individuals with limb loss worldwide (Farina & Aszmann, 2014).

2. Background

The evolution of prosthetic technology has been a cornerstone of efforts to improve the quality of life for individuals with limb loss. Traditionally, prosthetic limbs were basic mechanical devices that performed simple functions, such as providing support or facilitating walking. However, over time, technological advancements have led to the development of **myoelectric prosthetics**, which use **electromyographic (EMG) sensors** to detect electrical activity from the user's residual muscles. These signals are then used to control the movement of the prosthetic limb, allowing for more sophisticated and natural motion, such as grasping, releasing, and even more complex tasks (Englehart & Hudgins, 2003). While these systems have improved the functionality of prosthetics, they come with significant **cost** and **complexity**, which can limit their accessibility, especially in low-income or resource-constrained environments.

2.1 The Need for Affordable Prosthetic

Prosthetic devices, particularly myoelectric ones, remain expensive, and many individuals in developing countries or lower-income communities are unable to afford them. A typical **myoelectric prosthetic limb** can cost thousands of dollars, a price that includes not just the device itself but also the maintenance and fitting processes, which are often prohibitively expensive. Studies have emphasized the importance of developing **affordable prosthetic solutions** that can cater to a wider demographic, particularly in settings where access to healthcare and advanced medical devices is limited (Ten Kate et al., 2017).

Recent trends in prosthetic research have shifted towards exploring simpler, yet still effective, alternatives that can provide **basic functionality** while reducing **costs** and **complexity**. As prosthetic technology continues to evolve, researchers are investigating innovative solutions such as **Bluetooth-based control systems** and **3D printing**, which offer opportunities to develop low-cost and easy-to-use prosthetic devices. This shift in focus reflects a broader goal of democratizing access to prosthetic technology, ensuring that individuals with limb loss can benefit from functional prosthetics without the financial and technical barriers typically associated with current systems (Farina & Aszmann, 2014).

2.2. Bluetooth-Controlled Prosthetics

Bluetooth technology has become a cornerstone of many modern **assistive devices** due to its **low-cost**, **low-power**, and **short-range communication** capabilities. In prosthetic development, Bluetooth offers a convenient method for enabling wireless control of prosthetic limbs. **Bluetooth-based control** systems allow users to wirelessly interact with their prosthetic devices through **smartphones** or other Bluetooth-enabled devices, offering a more **user-friendly** and **intuitive control method** compared to traditional systems that rely on physical switches or sensors.

Several studies have highlighted the potential for Bluetooth communication to replace or complement traditional wired and sensor-based control systems. A

Bluetooth module, such as the **HC-05** module used in this project, allows seamless integration with smartphones or microcontrollers, enabling real-time control of prosthetic movements. This type of control is advantageous because it removes the need for **wired connections**, allowing for greater **mobility** and eliminating the risks associated with tethered systems (Salmond et al., 2020).

2.3. The Role of 3D Printing in Prosthetics

In recent years, **3D printing** has emerged as a transformative tool in the creation of prosthetics. This technology enables the rapid production of **customizable prosthetic components** at a significantly lower cost than traditional manufacturing methods. With 3D printing, prosthetic parts can be designed and fabricated with a high degree of **personalization**, ensuring that the device fits the individual's body and needs perfectly. Furthermore, 3D-printed prosthetics can be easily **repaired** or **modified**, making them more **sustainable** and **adaptable**.

The use of 3D printing in prosthetic design also enables **rapid prototyping**, which can facilitate iterative testing and development of new prosthetic components. This is particularly beneficial for individuals with unique anatomical requirements or for those who need frequent adjustments or replacements. By combining 3D-printed prosthetic components with a **Bluetooth-based control system**, the proposed system offers an affordable and customizable prosthetic arm that can be easily adapted to the user's specific needs.

2.4. Previous Work and Technological Innovations

Numerous studies have been conducted to explore alternative control mechanisms and design features for **low-cost prosthetics**. For example, researchers have developed **Bluetooth-controlled prosthetic arms**, which allow for easier control through mobile devices and significantly reduce the need for costly EMG sensors and other complex hardware. The use of **AVR Microcontroller systems** has also been explored as a way to provide a more **cost-effective**, **open-source**, and **easily customizable** solution for prosthetic control (Ten Kate et al., 2017).

Previous work has demonstrated that with the integration of **Bluetooth** and **AVR microcontrollers**, it is possible to create prosthetic arms that offer basic functionality such as **grasping, holding**, and **releasing** objects. While these systems do not offer the same level of **dexterity** or **fine motor control** as more expensive myoelectric prosthetics, they are an excellent option for individuals who need a basic but functional prosthetic at a fraction of the cost. These innovations provide a **starting point** for further exploration into how **Bluetooth and smartphone technologies** can be leveraged to enhance the affordability and functionality of prosthetic limbs, particularly for individuals in underserved regions (Salmond et al., 2020).

3. Key Features of the Proposed System

The proposed system presents a low-cost, myoelectric prosthetic arm designed with a focus on accessibility, simplicity, and practical functionality. By leveraging **Bluetooth-based mobile app control**, this design addresses critical limitations in affordability and complexity observed in traditional prosthetic systems (Farina & Aszmann, 2014; Englehart & Hudgins, 2003). The system provides a realistic solution for amputees, especially in low-resource settings, by prioritizing cost-effectiveness and user-friendliness without sacrificing core utility.

3.1 Cost-Effective Electronic Components

The system uses microcontroller, **MG996R servo motors** for actuation, and the **HC-05 module** for wireless connectivity. All components are **readily available and low-cost**, contributing to an overall system cost of under **$200 USD (**~₹ 20,000), aligning with global accessibility goals for prosthetics (WHO, 2017). The choice of these components ensures ease of sourcing and repair, making the design scalable and replicable in resource-constrained regions

3.2 Bluetooth-Based Mobile App Control (HC-05)

A central innovation of this prosthetic arm is its use of the **HC-05 Bluetooth module**, which establishes a reliable wireless communication link with a smartphone. The mobile app interface allows users to send control commands (e.g., open or close hand) seamlessly to the arm in real-time. This approach eliminates the need for complex signal processing and enables **greater mobility and control accessibility**, especially for users unfamiliar with advanced biosignal systems (Salmond et al., 2020).

3.3 Modular and 3D-Printed Design

The mechanical design features a **fully 3D-printed frame** constructed with PLA material, which is both lightweight and structurally reliable. Components such as fingers, joints, and servo mounts are modular, allowing for easy customization and replacement. This approach reduces repair time and increases serviceability, consistent with best practices for low-cost prosthetics (Ten Kate et al., 2017).

3.4 Simple User Interface

The **mobile application interface** provides a clean and intuitive control platform. Instead of relying on muscle signals or external sensors, users interact with basic buttons on their smartphone to initiate specific movements. This design simplifies training and reduces the learning curve, making the system ideal for **first-time users or non-technical users**, as supported by findings in prosthetic usability research (Resnik et al., 2018).

3.5 Basic Functional Capabilities

Despite its simplicity, the arm can perform essential functions like:

- **Opening and closing grip**
- **Holding light objects (up to 2.5 kg)**
- **Performing daily tasks such as holding utensils or cups**

These functionalities meet core needs for prosthetic users who prioritize **affordable, functional assistance** over complex multi-degree articulation (Castellini & Ravindra, 2014).

3.6 Rapid Deployment and Maintenance

The full system can be **assembled in under three hours**, requiring minimal tools and technical skills. The modular build also means that damaged or worn components can be replaced easily without discarding the entire unit. These features make the arm suitable for use in **emergency medical camps, rural clinics**, or post-disaster recovery zones (WHO, 2017).

3.7 Scalability for Future Enhancements

The system architecture is designed to support **future upgrades**, including:

- BLE (Bluetooth Low Energy) communication for longer battery life
- Integration of simple **gesture or voice recognition modules**
- Addition of **sensory feedback mechanisms** (e.g., pressure sensors)

These pathways support long-term improvement while maintaining the core value of affordability and simplicity (Farina & Aszmann, 2014).

4. Proposed Methodology

The development of the proposed low-cost prosthetic arm was guided by a user-centric, modular engineering approach emphasizing **simplicity, accessibility, and replicability**. Unlike conventional myoelectric prostheses that rely on complex biosignal acquisition and EMG processing (Englehart & Hudgins, 2003; Farina & Aszmann, 2014), this design prioritizes **cost-effective, non-biological control** using a **Bluetooth-enabled mobile application**. The following subsections outline the methodology followed in the system development, from concept to functional prototyping.

4.1 Block Diagram

4.2 System Architecture Overview

The system architecture consists of four core subsystems:

- **Mobile Application Interface** (Android-based)
- **Wireless Communication Module** (HC-05 Bluetooth)
- **Microcontroller Platform** (AVR Board)
- **Mechatronic Actuation Unit** (Servo-driven 3D-printed prosthetic arm)

Each of these blocks interacts in real-time to translate user commands into motor actuation, enabling basic prosthetic functionalities such as **grip open/close**. The absence of EMG sensors reduces design complexity and lowers production cost, making the system ideal for deployment in low-resource environments (WHO, 2017).

4.3 Hardware Workflow

4.3.1 Bluetooth Communication

The HC-05 Bluetooth module acts as the **wireless bridge** between the mobile app and the microcontroller. The mobile application transmits predefined ASCII commands (e.g., "A" for grip close, "B" for grip open), which are parsed by the AVR Microcontroller to control servo motor actuation.

- **Communication Protocol:** Serial UART @ 9600 bps
- **Range:** ~10 meters (line-of-sight)

This wireless approach provides a **cleaner, less intrusive control interface**, eliminating the discomfort and inconsistencies associated with EMG electrode placement (Salmond et al., 2020).

4.3.2 **Microcontroller and Servo Control**

The AVR Microcontroller is programmed to:

- Initialize Bluetooth communication
- Parse incoming commands
- Trigger specific PWM signals to **MG996R servo motors** to drive finger articulation

Each motor corresponds to a joint in the prosthetic hand (typically thumb and fingers), enabling grip motion using a **preset angular range (0°–180°)**.

4.3.3 **Power Supply**

A **7.4V Li-Po battery** (2-cell) powers the system, stepped down and regulated for servo and AVR Microcontroller logic voltage levels.

4.4 Software Methodology

4.4.1 **Mobile Application**

The Android app (developed in MIT App Inventor) contains:

- On-screen buttons labeled "Open Hand", "Close Hand" and specific finger movements.
- Bluetooth connection status display
- Error handling for lost connection

Once paired with the HC-05 module, button presses generate control characters that are transmitted in real-time. The application is lightweight and optimized for offline use, improving usability in remote locations (Castellini & Ravindra, 2014).

4.5 **Mechanical Design Approach**

The mechanical assembly was modeled in **Fusion 360** and printed using **PLA filament**. The prosthetic hand includes:

- Articulated fingers driven by servo-pulley systems
- A wrist mount with Velcro straps for socket attachment
- Internal housing for electronics and battery

3D printing allows **easy customization and part replacement**, aligning with low-cost fabrication standards (Ten Kate et al., 2017).

5. System Design and Implementation

The goal of this project is to develop a low-cost prosthetic arm controlled through wireless signals using the **HC-05 Bluetooth module**. The prosthetic is operated through predefined commands transmitted from an external device (e.g., mobile phone or microcontroller-based switch) using Bluetooth technology. This simplifies the hardware design, reduces cost, and increases accessibility—particularly in developing regions where conventional myoelectric solutions are prohibitively expensive (Resnik et al., 2018; WHO, 2017).

5.1 System Overview

The system architecture is divided into the following core modules:

- **Input and Control Device** (e.g., smartphone, custom-built switch)
- **Wireless Communication Module** (HC-05 Bluetooth)
- **Microcontroller**
- **Motor Driver**
- **Actuators (Servo Motors)**
- **3D-Printed Prosthetic Structure**
- **Battery and Power Regulation Circuit**

This modular approach ensures simplicity and low cost while providing reliable performance suitable for real-world use.

5.2 Input and Command Transmission

The user issues commands manually via a **smartphone application** with a simple button interface, or a **custom remote controller** consisting of buttons connected to a microcontroller.

Each button or app command corresponds to a specific movement, such as: Grip, Release, Open hand, Close hand

These commands are sent via **Bluetooth serial communication** using the **HC-05 module**, a popular and inexpensive component that supports stable wireless data transfer over short ranges (~10 meters) (Salmond et al., 2020).

5.3 Bluetooth Communication Interface

The **HC-05 Bluetooth module** is configured as a slave device connected to the microcontroller mounted on the prosthetic arm. It listens for serial input from the remote control or app. Each unique command triggers a pre-programmed response by the prosthetic's onboard controller.

Unlike BLE modules, HC-05 offers a more stable connection for continuous streaming of commands in basic prosthetic applications

5.4 Microcontroller-Based Control Unit

The brain of the prosthetic arm is a **microcontroller**, which receives serial data from the HC-05. Based on the received character, it executes the corresponding motor control logic. This is achieved using Pulse Width Modulation (PWM) signals to actuate servo motors embedded within the hand.

The benefits of using AVR Microcontroller include: Low power consumption, Wide community support, Open-source development environment. Additionally, these microcontrollers allow for future expansion such as feedback loops, sensory integration, or mobile app support (Englehart & Hudgins, 2003)

5.5 Actuation Mechanism

Upon receiving a command, the microcontroller drives servo motors placed inside the prosthetic hand to simulate finger movements. Nylon tendons or fishing lines are used to transmit motion from the servo to the fingers, which are jointed and tensioned to return to the resting state when not actuated.

Movements supported include: **Flexion and extension** of fingers for gripping, **Opening and closing** the palm, Optional **wrist rotation**, if additional actuators are added

Each movement is mapped to a Bluetooth command and executed via the control unit's firmware logic (Ten Kate et al., 2017).

5.6 Mechanical Design and 3D Printing

The structural components of the prosthetic are designed using CAD software and fabricated using **Fused Deposition Modeling (FDM)** 3D printing technology. PLA (Polylactic Acid) is used due to its lightweight, durability, and low cost. The palm, fingers, and wrist are printed in modular segments, allowing easy maintenance and part replacement.

Mechanical design features: Hinged joints for finger motion, Palm chamber for servo and wiring placement, Universal cuff/socket to fit varying forearm sizes (Farina & Aszmann, 2014).

5.7 Power Management

A **7.4V Li-Po battery** is used to power the entire system. Voltage regulators ensure the correct power levels for logic (5V or 3.3V) and servos (5–6V). The total power consumption is kept low to ensure 3–5 hours of active usage per charge.Optional features such as sleep modes or idle timeouts are implemented in the microcontroller firmware to conserve energy

5.8 Calibration and Testing

System testing is divided into three stages:

- **Connectivity Testing**: Ensuring stable Bluetooth pairing and command reception.
- **Motion Accuracy Testing**: Checking the reliability and repeatability of servo actuation.
- **User Interaction Testing**: Simulated trials with test users to evaluate ergonomic fit and control ease.

Although not controlled through EMG, this methodology provides high responsiveness and allows users with minimal training to operate the prosthetic arm efficiently (Castellini & Ravindra, 2014; Resnik et al., 2018)

6. Objectives

The overarching objective of this research is to develop an **affordable, user-friendly, and non-invasive prosthetic arm** that can be wirelessly controlled using **Bluetooth communication**. This design is targeted at improving accessibility and functional independence for individuals with upper limb amputations, especially in **low- and middle-income regions** where commercial bionic limbs are financially inaccessible (WHO, 2017; Resnik et al., 2018).

To achieve this, the project defines the following **specific objectives**:

6.1 Design a Cost-Effective and Modular Prosthetic Limb

To design a **prosthetic arm** using **low-cost, readily available components**, including open-source microcontrollers, servo motors, and 3D-printed parts. Ensure that the **total cost** of the device remains under **$500 USD**, in contrast to conventional myoelectric arms that may cost between ₹20,000–₹50,000 (Resnik et al., 2018; Ten Kate et al., 2017).

6.2 **Implement a Bluetooth-Based Wireless Control System**

To integrate a **Bluetooth HC-05 module** with a microcontroller for **wireless transmission of control commands** from a smartphone app or remote control. Evaluate the performance of HC-05 in real-time command reception, signal stability, and latency (Salmond et al., 2020).

6.3 **Ensure Functional Performance and Mechanical Reliability**

To build and test a mechanical arm structure using **3D printing (PLA material)** that supports basic hand movements while maintaining lightweight ergonomics (Ten Kate et al., 2017). Evaluate the mechanical durability of components and their compatibility with daily activities like holding objects, making gestures, and gripping items of varied sizes and textures.

6.4 **Promote Sustainable Development Goals in Assistive Technology**

Align the project with global health and technology equity goals by developing an **inclusive and sustainable assistive device**, reinforcing the **World Health Organization's call** for increased investment in prosthetic accessibility (WHO, 2017).

7. Results and Performance

This section presents the **experimental results, performance benchmarks**, and **usability assessments** of the developed low-cost myoelectric prosthetic arm. All results are framed in the context of the project objectives and validated through iterative testing, real-world simulations, and peer-reviewed comparison standards.

7.1 Functional Performance Testing

7.1.1 **Response Time and Wireless Control**Using the **HC-05 Bluetooth module**, the average time delay between issuing a command from the control interface

(Android app or button pad) and actuation of the prosthetic fingers was measured at **<150 ms**, which is within acceptable limits for real-time control applications (Salmond et al., 2020). The HC-05 demonstrated stable connectivity within a **10-meter range**, with negligible signal loss or command duplication under standard indoor conditions.

Compared to commercial BLE solutions, the HC-05 showed Higher power consumption (~30 mA idle), but easier configurability and better compatibility with low-end microcontrollers.

7.1.2 Motion Fidelity and Repeatability

The prosthetic hand was programmed to execute basic gestures: **open hand**, **close hand**, and **grip**, each mapped to unique Bluetooth commands. Testing over 200 actuation cycles showed:

- **97.5% accuracy** in motor response to input commands.
- Minimal mechanical drift over time.
- Consistent grip strength of ~1.8 N using standard servo motors (MG996R).

The actuation fidelity remained consistent across sessions, with less than **±5° error** in finger angular movement between repeated operations—comparable to metrics in low-end commercial prostheses (Resnik et al., 2018; Ten Kate et al., 2017).

7.2 Mechanical and Structural Assessment

7.2.1 Material Durability

The prosthetic arm was fabricated using **3D-printed PLA** components. Under static loads of **up to 2.5 kg** (carried in a hanging grip), the fingers maintained structural integrity without deformation or warping. Drop tests from 1 meter showed no critical component failure, confirming the mechanical resilience required for day-to-day use (Ten Kate et al., 2017).

***7.2.2* Modular Assembly and Maintenance**

One of the design goals was modularity. Each servo motor, tendon, or finger segment could be individually removed and replaced within **15 minutes**, allowing for cost-effective repair in field conditions. This design approach aligns with WHO's recommendation for **sustainable and locally maintainable prosthetic systems** (WHO, 2017).

7.3 Power Efficiency and Battery Life

With a **7.4V 1000mAh Li-Po battery**, the system could operate continuously for approximately **3.5 hours** under normal usage (60% active time, 40% idle). Idle current draw was measured at ~20 mA, and peak current during actuation reached 800 mA.

Future optimizations such as servo power gating and low-power sleep modes in the microcontroller could increase operational time by up to **25%**, making it more viable for extended daily use in remote regions (Castellini & Ravindra, 2014).

7.4 Challenges and Limitations

Despite the potential benefits, Bluetooth-controlled prosthetic systems face several challenges. **Signal interference** and **communication range** limitations are potential obstacles in ensuring reliable operation, particularly in environments where the user is moving or interacting with various objects. Additionally, power consumption is a concern, as the Bluetooth module and servos that drive the prosthetic arm require a steady power supply. To address these issues, efficient **battery management** and **low-power communication** techniques must be incorporated into the design to maximize the system's performance (Salmond et al., 2020).

Furthermore, while Bluetooth control offers simplicity, it still requires the user to have access to a compatible **smartphone** and the necessary **mobile app**. This could be a limitation in certain settings where smartphones are not readily available, or where users may have difficulty navigating smartphone interfaces. Thus, additional considerations for accessibility and ease of use will be important in the development of the mobile app and the prosthetic control system.

While the system meets its primary goals, a few limitations were observed:

- Lack of **proportional control** (no variable grip strength)
- Absence of **sensory feedback** (tactile or pressure sensing)
- Limited **degrees of freedom**, restricted to basic grasp functions
- Not tested with actual amputee users due to ethical and clinical constraints

7.5 Summary of Performance Metrics

Table 1. Performance Metrics

Parameter	**Measured Value**
Average Response Time	<150 ms
Actuation Accuracy	97.5%
Grip Force	~1.8 N
Operational Battery Life	~3.5 hours
Build Cost	~$200 USD (~₹20,000)
Structural Load Capacity	~2.5 kg
Control Interface	Bluetooth (HC-05)

The proposed **low-cost Bluetooth-controlled prosthetic arm** represents a significant step toward providing **affordable and functional prosthetics** to individuals with limb loss. By integrating Bluetooth technology, 3D-printed components, and an AVR Microcontroller-based control system, the project offers a simple, cost-effective alternative to traditional myoelectric prosthetics. This work builds upon previous research and innovation, aiming to reduce the **cost**, **complexity**, and **inaccessibility** of advanced prosthetic systems, and provides a practical solution for improving the lives of individuals with limb loss. The subsequent sections of this paper will outline the **proposed methodology**, **design implementation**, and **evaluation** of the system, further demonstrating its potential for real-world application.

8. Conclusions

The development of a **low-cost, Bluetooth-controlled myoelectric prosthetic arm**—without relying on traditional **EMG sensors**—has proven to be a feasible and impactful approach toward democratizing assistive technologies. The system successfully balances affordability, functionality, and accessibility while circumventing the cost and complexity of EMG signal acquisition and processing, as noted in previous studies (Farina & Aszmann, 2014; Englehart & Hudgins, 2003).

This research demonstrated that a **Bluetooth HC-05–based wireless control interface**, combined with modular 3D-printed components and basic servo-driven actuation, can effectively support essential hand functions such as **grasping and releasing**. The prosthetic arm showed strong performance in terms of **response time (<150 ms)**, **mechanical durability**, and **control accuracy (~97.5%)**, aligning with WHO guidelines for essential assistive devices in low-resource settings (WHO, 2017).

While commercial prosthetic systems often provide **multi-gesture capability**, **proportional control**, and **haptic feedback**, they are largely inaccessible due to high costs and complex configuration requirements (Resnik et al., 2018; Ten Kate et al., 2017). In contrast, this project offers a pragmatic solution—particularly for users in underprivileged communities—by enabling straightforward control via a mobile app or button-based interface. This aligns with the vision of open-source, **sustainable prosthetic technologies** advocated by Castellini & Ravindra (2014) and supports WHO's call for **inclusive design** in rehabilitative care (WHO, 2017).

However, it must be acknowledged that **certain limitations remain**. The system currently lacks proportional control, multi-degree articulation, and sensory feedback—features that are vital for fully biomimetic interaction and advanced prosthetic functionality (Farina & Aszmann, 2014). Moreover, actual testing with amputee users was beyond the scope of this project due to ethical and clinical constraints.

Despite these limitations, the results affirm that **reliable and functional prosthetic solutions can be engineered using low-cost, off-the-shelf technologies** when guided by inclusive and sustainable design principles. The modular architecture ensures future adaptability—such as upgrading to BLE modules, integrating gesture sensors, or adding sensory input—while retaining the system's core affordability and usability benefits.

In summary, this project stands as a **viable proof-of-concept for next-generation low-cost prosthetics**. It contributes to a growing body of research that seeks to **bridge the gap between affordability and functionality** in the domain of upper limb prosthetics. The findings support the premise that **wireless, EMG-free control mechanisms** can serve as practical alternatives to traditional systems, especially when tailored for underserved populations and constrained environments (Salmond et al., 2020; Ten Kate et al., 2017).

Future work will focus on clinical testing with actual amputees, integration of machine learning for gesture recognition, and refinement of ergonomic and sensory feedback features. By doing so, we aim to further reduce the disparity in access to high-quality rehabilitative technology around the world.

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