

Design and Implementation of a Low-Cost Prosthetic Twin System for Real-Time Motion Replication using ESP-NOW

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ABSTRACT: The loss of upper-limb functionality significantly affects an individual's ability to perform everyday activities, creating a growing demand for affordable and accessible prosthetic solutions. This paper presents the design and implementation of a low-cost Prosthetic Twin System capable of real-time motion replication using embedded systems and wireless communication technologies. The developed system consists of two identical prosthetic hand units in a master–slave architecture. User input is provided through a smartphone interface communicating with the master unit via ESP32, while motion commands are transmitted wirelessly to the slave unit using the ESP-NOW protocol for real-time synchronization. The prosthetic hand utilizes an underactuated tendon-driven mechanism with MG996R servo motors and cable-driven actuation through 3D printed ABS finger structures. The system integrates a PCA9685 PWM driver, INA219 current sensor, OLED display, and LiPo battery management subsystem. Experimental testing demonstrated synchronized finger flexion, extension, and basic grasping with 20–40 ms communication latency and stable operation within a 5–10 metre range. The prototype demonstrates the feasibility of a physical digital twin architecture for prosthetic applications using commercially available low-cost components.

KEYWORDS: Prosthetic Hand, Digital Twin, ESP32, ESP-NOW, Underactuated Mechanism, Tendon-Driven Actuation, Real-Time Synchronization, Embedded Systems.

I. INTRODUCTION

The loss of a limb significantly affects an individual's quality of life, limiting independence and the ability to perform everyday tasks. Prosthetic technologies aim to restore functionality; however, many advanced solutions remain expensive and inaccessible to a large portion of the global population [9]. In parallel, advancements in robotics and communication systems have enabled the development of more intelligent and connected assistive devices [3].

Among these, the concept of a digital twin has gained attention as a method for achieving real-time synchronization between physical systems [5]. In the context of prosthetics, this concept can be extended beyond virtual simulation to enable physical replication of motion across multiple devices. This project focuses on the development of a prosthetic twin system in which two identical prosthetic hands are synchronized using a master–slave architecture. User inputs are provided via a smartphone interface and transmitted wirelessly to a master unit, which then communicates motion commands to a secondary unit using ESP-NOW, enabling real-time mirroring.

II. LITERATURE REVIEW

2.1 Evolution of Prosthetic Systems

The development of prosthetic and robotic hands has advanced significantly over the years in response to the need to restore functionality and quality of life for individuals with upper-limb loss. Early prosthetic systems were limited to passive or body-powered devices, whereas recent developments have introduced electrically actuated and myoelectric prostheses with improved motion capability [9]. Despite these advancements, challenges such as high cost, mechanical complexity, limited accessibility, and difficult user control continue to restrict widespread adoption [1].

2.2 Classification of Prosthetic Hands

Modern prosthetic systems are commonly classified as passive, body-powered, or externally powered devices. Among externally powered prostheses, myoelectric hands have gained importance as they allow actuation through electrical signals derived from muscle activity. However, such systems often require calibration, signal interpretation, and specialized components, which increase cost and operational complexity [9]. As a result, there is continued interest in simpler and more affordable control strategies [8].

2.3 Mechanical Design and Underactuation

The human hand is a highly complex structure with multiple joints and degrees of freedom. Many prosthetic designs use mechanically coupled systems where multiple joints are driven by a single actuator, reducing complexity but limiting dexterity. To address this, underactuated mechanisms have been developed in which fewer actuators control multiple joints using tendon-driven or cable-based systems [1]. These designs reduce weight and cost while improving adaptability, though they introduce trade-offs in precision and control [2].

2.4 Tendon-Driven Actuation Systems

Tendon-driven systems have been widely used in prosthetic design due to their ability to mimic human muscle-tendon behaviour. In these systems, motors generate rotational motion that is converted into cable tension, causing coordinated finger flexion [4]. This method is well suited for compact and lightweight designs, although factors such as friction, cable routing, and return mechanisms must be carefully managed [8].

2.5 Digital Twin and Wireless Communication in Robotics

The concept of digital twins has gained importance in robotics and mechatronics. Traditionally associated with virtual simulations, digital twin principles can also be applied to physical systems through real-time synchronization [3]. A master-slave architecture enables one system to transmit control signals to another to achieve mirrored motion. Wireless communication technologies such as Wi-Fi, Bluetooth, and ESP-NOW enable low-latency data transmission, making real-time synchronization feasible [5]. The ESP32-based digital twin system by Zheng and Chen [5] demonstrated virtual-real consistency with sub-2° mapping errors, highlighting the viability of ESP32 for such applications.

2.6 Gaps Identified

Despite advancements in prosthetic technology, most advanced systems remain expensive and rely on complex control mechanisms such as EMG signals, which require calibration and expertise [9]. There is limited work on real-time synchronization between two physical prosthetic systems using low-cost hardware. Existing digital twin implementations are largely focused on virtual simulations rather than physical replication [3][5]. These gaps highlight the need for a simple, cost-effective prosthetic system capable of real-time mirrored operation using accessible technologies.

III. OBJECTIVES

The primary objectives of this project are:

- (i) To design and develop a low-cost prosthetic hand using an underactuated mechanism.
- (ii) To implement a master-slave architecture for real-time motion replication.
- (iii) To integrate smartphone-based control with embedded systems.
- (iv) To establish wireless communication using the ESP-NOW protocol.
- (v) To develop a functional prosthetic twin system capable of synchronized operation.

IV. METHODOLOGY AND SYSTEM DEVELOPMENT

The development of the prosthetic twin system was carried out through a structured approach involving mechanical assembly, electronic integration, and communication design. An existing open-source CAD model of a tendon-driven prosthetic hand was selected and fabricated using 3D printing. All required components, including actuators, control modules, and power systems, were procured, individually tested, and then assembled into the complete system.

The system consists of two identical prosthetic units configured in a master-slave architecture. User input is provided through a smartphone interface, which communicates with the master ESP32 unit. The master unit processes these

inputs and generates corresponding control signals for finger actuation, which are then transmitted to the slave unit using the ESP-NOW protocol for real-time motion replication [5].

4.1 Selection and Fabrication of CAD Model

The initial stage involved selection and fabrication of a suitable CAD model for the prosthetic hand. A survey of available open-source designs was conducted, focusing on models incorporating tendon-driven or pulley-based actuation mechanisms. Key selection criteria included structural similarity to a human hand, ease of assembly, compatibility with servo-driven actuation, provision for cable routing, and suitability for FDM 3D printing [4]. The selected model was fabricated in ABS, which was chosen over PLA due to its improved wear resistance, strength, and elastic recovery under repeated cyclic joint motion [6].

4.2 Component Selection and Specifications

Following fabrication, all required components were identified and selected based on system requirements. The system was built around the ESP32 microcontroller with a PCA9685 PWM driver for servo control and MG996R servo motors for actuation. Additional components included an INA219 current sensor, OLED display, LiPo battery, and a buck converter for voltage regulation. All components were tested individually to verify functionality before full system integration. Table 1 summarizes the component specifications.

Table.1. Component Specifications

Component	Specification	Qty	Purpose
ESP32	WiFi + BLE MCU	2	Control & communication
PCA9685	16-channel PWM driver	1	Servo control
MG996R Servo	High torque (~10 kg·cm)	3	Finger actuation
INA219	Current/Voltage sensor	1	Battery monitoring
OLED Display	128×64 I2C	1	Status display
LiPo Battery	2200 mAh	1	Power supply
Buck Converter	Step-down regulator	1	Voltage regulation

4.3 Mechanical Design and Actuation Mechanism

The actuation system uses an underactuated tendon-driven mechanism with three MG996R servo motors controlling five digits. The index–middle and ring–pinky fingers are grouped while the thumb is independently actuated. High-strength monofilament fishing line is used as the artificial tendon, routed through finger segments and connected to motor-driven spools. Flexion is achieved through cable tension, while extension relies on the structural elasticity of the printed joints, eliminating the need for return springs [1][2]. Table 2 shows the motor-to-finger assignment.

Table.2. Motor-to-Finger Assignment

Motor	Controlled Fingers
Motor 1	Index + Middle
Motor 2	Ring + Pinky
Motor 3	Thumb



Fig.1. Physical Model of the Palm and Fingers with Fishing Lines as Tendons

The parametric configuration of the assembled system is summarized in Table 3.

Table.3. System Parametric Values

Parameter	Value
Number of Fingers	5
Number of Actuators	3
Control Method	Smartphone + ESP32
Communication Protocol	ESP-NOW
Power Source	2200 mAh LiPo
Material	ABS
Actuation Type	Cable-driven (underactuated)

4.4 Electronic Design and Digital Twin Architecture

The system architecture is based on a physical digital twin model, where a secondary prosthetic unit mirrors the motion of the master unit in real time [3][5]. Rather than relying on sensor-based motion tracking, the system directly replicates control signals across both units, minimizing latency and avoiding errors from sensor noise or signal processing. The initial implementation used an Arduino Nano with an HC-05 Bluetooth module but was upgraded to an ESP32-based architecture due to latency and reliability issues.

For inter-device communication, the ESP-NOW protocol was adopted. This connectionless, peer-to-peer protocol enables low-latency data transmission without requiring traditional network infrastructure [5]. The electrical system includes the ESP32, PCA9685 PWM driver, MG996R servos, INA219 current sensor, LiPo battery, buck converter, and OLED display. Battery state-of-charge is estimated from INA219 measurements and stored using EEPROM emulation to ensure persistence across power cycles, with the value displayed on the OLED.

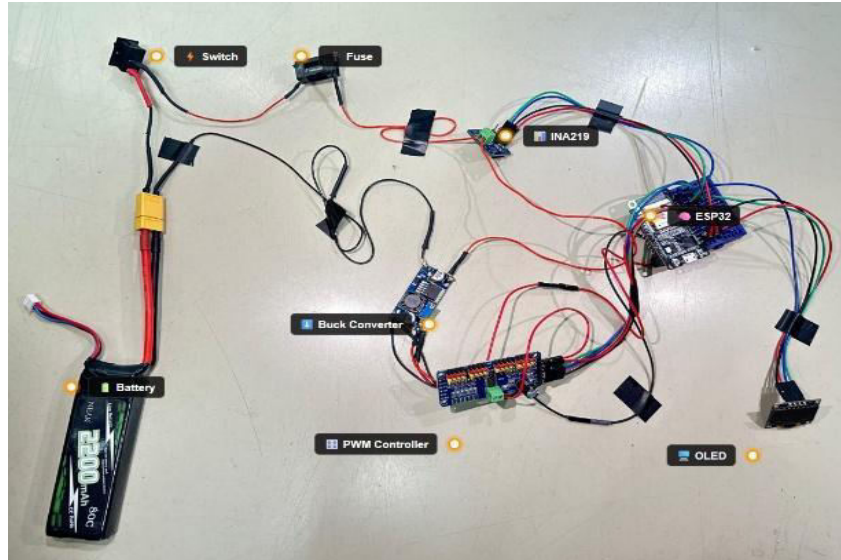


Fig.2 (a) Electrical Schematic of the Circuit

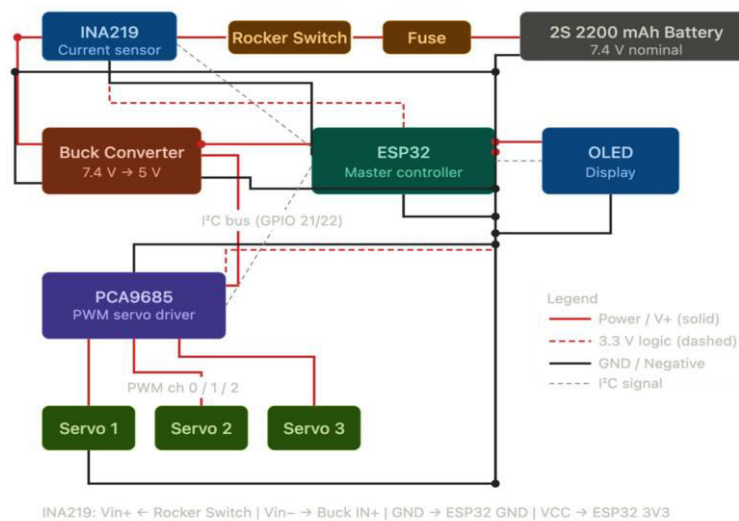


Fig.2 (b) Electrical Schematic of the Circuit (continued)

V. DESIGN CONSTRAINTS

5.1 Mechanical and Fabrication Constraints

The achievable dimensional tolerance of FDM 3D printing presented a primary constraint. The initial CAD model resulted in interference fits at joint interfaces and inadequate clearances in cable routing channels, necessitating a full model transition. Even with the improved model, the inherent layer-adhesion anisotropy of FDM-printed parts required careful orientation during slicing to ensure structural loads were applied along the strongest axis.

FDM-printed PLA lacked the wear resistance required at joint interfaces subjected to continuous cyclic motion. Transitioning to ABS resolved this by providing a harder, tougher surface. However, ABS requires a heated enclosure to prevent warping, demanding more precise process control [4][6]. The underactuated configuration imposes a functional constraint on independent finger control; the coupled grouping of fingers was accepted as a deliberate trade-off in favour of mechanical simplicity and affordability.

5.2 Power and Energy Management Constraints

Power management presented a significant constraint, given the use of a single 2200 mAh LiPo cell to power the entire system. MG996R servo motors draw considerable instantaneous current under load, particularly during simultaneous multi-finger actuation. A buck converter providing a stable regulated voltage rail to all logic circuitry addressed this by isolating sensitive control electronics from actuator transient demands.

To prevent mid-operation system failure, the battery monitoring subsystem was designed as a proactive safeguard. The INA219 module provides continuous measurement of battery terminal voltage and current, from which the ESP32 computes a state-of-charge estimate that is periodically written to EEPROM. The resulting real-time battery percentage displayed on the OLED gives the user reliable advance warning of low charge conditions.

5.3 Communication and Latency Constraints

Real-time mirroring places a stringent requirement on communication latency. The initial Bluetooth Classic implementation via the HC-05 module exhibited variable latency and occasional packet loss that introduced visible desynchronization between the two units. The transition to ESP-NOW resolved this by eliminating connection-establishment overhead inherent to standard Bluetooth and TCP/IP stacks [5]. Operating as a connectionless peer-to-peer protocol over the 2.4 GHz band, ESP-NOW achieves consistent packet delivery latencies of a few milliseconds.

By transmitting the same PWM command data simultaneously to both units, the system sidesteps sensor acquisition, filtering, and processing stages, achieving synchronization at the signal level. This architectural choice is therefore not merely a simplification but a deliberate technical response to the latency and accuracy constraints of real-time digital twin operation [3].

VI. RESULTS AND DISCUSSION

6.1 System Functionality and Validation

The integrated master–slave prosthetic twin system successfully demonstrated real-time motion replication across all fundamental test configurations. Input commands from the smartphone interface were processed by the master ESP32 unit and accurately mirrored by the slave unit. Empirical validation confirmed stable execution of synchronized finger flexion, extension, and coordinated object grasping across multiple continuous testing cycles, validating the kinematic integrity of the underactuated mechanism.

6.2 Motion Synchronization and Response Analysis

Motion synchronization was evaluated through repeated cyclic actuation. The ESP-NOW protocol eliminated session-management overhead typical of standard network architectures. Timing analysis established an average end-to-end communication latency of 20–40 ms — imperceptible during real-time human observation. Minor trajectory deviations occurred exclusively during rapid, high-frequency actuation due to the mechanical response limits of the servo motors.

6.3 Mechanical Performance

The underactuated cable-driven architecture achieved successful structural force transmission via high-strength monofilament tendons. System reliability proved highly sensitive to tendon pretensioning: insufficient tension introduced mechanical backlash and incomplete joint flexion, whereas excessive tension reduced motor efficiency. Optimized tensioning configurations yielded highly repeatable finger dynamics, and a mechanical tendon-locking system effectively mitigated cable slippage across extended cycles [1][2].

6.4 Communication System Performance

The communication subsystem maintained a robust wireless link by combining smartphone Wi-Fi inputs with a dedicated ESP-NOW peer-to-peer network. Packet loss remained negligible within a standard indoor operating radius of 5–10 metres. While structural barriers and RF interference marginally degraded responsiveness at extended distances, the system sustained stable real-time synchronization within its designated operational envelope [5].

6.5 Power Consumption and System Stability

Power consumption varied with actuation load, exhibiting an average current draw of 1.5–2.5 A under nominal multi-finger operations. Powered by a 2200 mAh LiPo battery, the prototype achieved a continuous operational duty cycle of

50–90 minutes. The step-down buck converter successfully decoupled control logic from actuator-induced voltage sags, ensuring thermal stability and preventing component failure.

Table.4. Observed System Performance Parameters

Parameter	Observed Value
Latency	20–40 ms
Communication Range	5–10 m
Current Consumption	1.5–2.5 A
Battery Life	50 min – 1.5 hr
Packet Loss	Negligible

Table.5. Test Case Results

Test Case	Result
Finger Flexion	Successful
Finger Extension	Successful
Object Grasp	Successful
Continuous Operation	Stable
Wireless Synchronization	Successful

Table.6. System Advantages and Limitations

Advantages	Limitations
Low cost	Limited finger independence
Real-time mirroring	No sensory feedback
Simple, accessible design	Minor residual latency
Easy to build and replicate	Limited manipulation precision

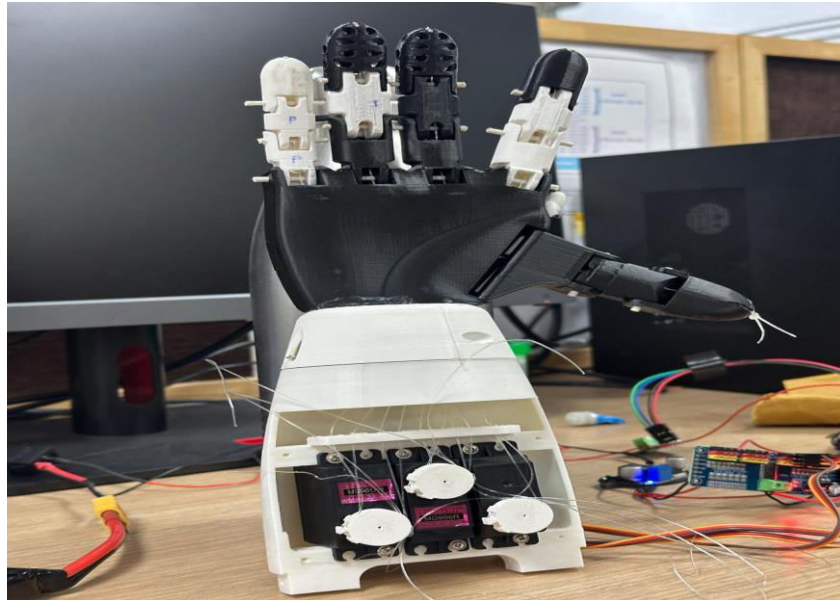


Fig.3. Assembled Model of the Prosthetic Hand (Open-Grip Configuration)

6.6 Limitations and Scope for Improvement

Despite successful implementation, certain limitations were identified. The absence of sensory feedback limits the system's ability to adapt to external forces or object interaction. The underactuated design restricts independent finger control, limiting dexterity. Minor communication latency, while small, could be further reduced through protocol optimization. Future improvements may include integration of tactile sensing, EMG-based control, improved mechanical design for increased dexterity, and development of a software-based virtual twin for enhanced monitoring and interaction [9][10].

6.7 Potential Applications

The developed system has potential applications in assistive technology, robotics, and teleoperation. It can serve as a foundation for low-cost prosthetic devices and training systems. The real-time mirroring capability also enables remote manipulation in controlled environments and can be used as an educational platform for demonstrating concepts in robotics, embedded systems, and human-machine interaction [3][5].

VII. CONCLUSION

This paper presented the design and implementation of a low-cost Prosthetic Twin System capable of real-time motion replication using ESP-NOW communication and embedded systems. The developed prototype successfully demonstrated synchronized operation between master and slave prosthetic units using an underactuated tendon-driven mechanism and wireless peer-to-peer communication. Experimental results confirmed stable operation, low communication latency of 20–40 ms, and reliable finger actuation using commercially available components.

The proposed system demonstrates the feasibility of implementing an affordable physical digital twin architecture for prosthetic and teleoperation applications. Future work may focus on improving finger dexterity, integrating tactile sensing and EMG-based control, and developing a software-based virtual twin for enhanced monitoring and interaction.

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