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Hybrid Control Prosthetic Finger: Underactuated Biomimetic Design With Voice And Flex Integration

A Low-Cost Biomimetic Approach for Adaptive Finger Prosthesis

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Abstract: In today's world designing prosthetic fingers remains a complex task, as achieving natural hand function often requires balancing biomimetic movement with mechanical simplicity. Existing prosthetic fingers often struggle to achieve both joint coupling and shape adaptation simultaneously, resulting in unnatural movement or reduced grip strength. The proposed work addresses these limitations through the design and prototyping of a biomimetic, underactuated finger mechanism (HyFi) actuated by a single DC motor via an inelastic tendon. This configuration enables coordinated motion across three joints (MCP, PIP, DIP) while minimizing mechanical complexity. The system is validated through CAD modeling, simulation, and 3D-printed prototyping. Additionally, a dual control approach using voice commands and a flex sensor is proposed to enhance user accessibility and interaction in future iterations. This addition is intended to enhance system adaptability and improve user interaction across different user conditions.

***Index Terms* -** Prosthetic finger, underactuated mechanism, tendon-driven actuation, voice control, flex sensor, biomimetic design.

I. INTRODUCTION

Loss of finger functionality significantly affects daily living activities such as grasping objects, holding tools, writing, or performing precise fine motor tasks. Even simple routine actions can become challenging without coordinated finger movement, reducing independence and overall quality of life. For this reason, the development of effective and accessible prosthetic solutions remains a critical focus in assistive and biomedical engineering.

Although prosthetic technology has advanced considerably in recent years, many existing systems remain either mechanically complex or financially inaccessible. Multi-motor prosthetic designs offer improved dexterity and independent joint control; however, they often increase overall weight, power consumption, structural complexity, and maintenance requirements. Such characteristics can limit comfort and long-term usability for everyday users. On the other hand, simplified mechanical designs aim to reduce cost and complexity but may compromise natural motion and adaptive grasping ability.

Biomimetic engineering provides a balanced alternative by drawing inspiration from the coordinated and adaptive movement of the human finger [1][2]. Underactuated mechanisms, in particular, enable multiple joints to be driven using fewer actuators. This allows passive adaptation to object shape during grasping while reducing mechanical and control complexity [5]. By minimizing actuator count and leveraging mechanical coupling, underactuated systems can achieve efficient and more natural motion without relying on highly complex control strategies [6][8].

In this context, the present work introduces a hybrid-controlled underactuated prosthetic finger that emphasizes mechanical simplicity, functional adaptability, and intuitive user interaction. By integrating tendon-driven actuation with user-friendly control interfaces such as voice commands and gesture-based sensing, the proposed system aims to provide a lightweight, affordable, and practical solution suitable for assistive rehabilitation and daily use.

II. SYSTEM OVERVIEW

The proposed prosthetic finger system is developed as an integrated assistive platform that combines mechanical design, sensing technology, and embedded control within a compact and cost-effective framework. The architecture emphasizes simplicity, functional reliability, and intuitive operation while avoiding unnecessary hardware complexity. As illustrated in Fig. 1, the overall system can be organized into four interconnected stages: input acquisition, signal conditioning, processing and decision-making, and actuation.

The input stage consists of two independent control mechanisms: voice-based control and gesture-based sensing. The voice recognition module allows the user to operate the prosthetic finger through predefined spoken commands such as “open” and “close.” This module processes the audio input internally and transmits a corresponding digital signal to the central controller. In parallel, gesture-based control is achieved using flex sensors embedded in a wearable glove. Each flex sensor varies its electrical resistance proportionally to the bending angle of the user’s finger [7]. These resistance variations are converted into measurable voltage signals through comparator or conditioning modules before being forwarded to the microcontroller.

At the core of the system is the ESP32 microcontroller, which functions as the central processing unit. It receives digital signals from the voice recognition module and conditioned analog signals from the flex sensor modules. The controller interprets these inputs based on predefined control logic and determines the appropriate actuation response. By integrating both discrete command-based input and proportional gesture-based input, the system allows flexible and adaptive interaction depending on the user’s preference or situational requirement.

The actuation stage is implemented using servo motors connected to the ESP32 through PWM-capable GPIO pins. The microcontroller generates Pulse Width Modulation (PWM) signals to precisely control the angular position of each servo. As the servo rotates, it pulls the tendon mechanism integrated within the prosthetic finger structure. The increase in tendon tension produces coordinated joint flexion, while elastic elements assist in passive return when the tension is released. This tendon-driven underactuated mechanism enables smooth and sequential finger motion using minimal actuator complexity.

A regulated power supply unit ensures stable voltage delivery to all electronic components, preventing performance degradation due to current fluctuations during motor operation. A push-button interface is also incorporated for system initialization and operational control.

Overall, the system architecture demonstrates a balanced integration of sensing, embedded processing, and biomechanical actuation [3]. By combining dual input strategies with a centralized microcontroller and a tendon-driven mechanical structure, the proposed design achieves adaptive finger movement while maintaining structural efficiency and affordability.

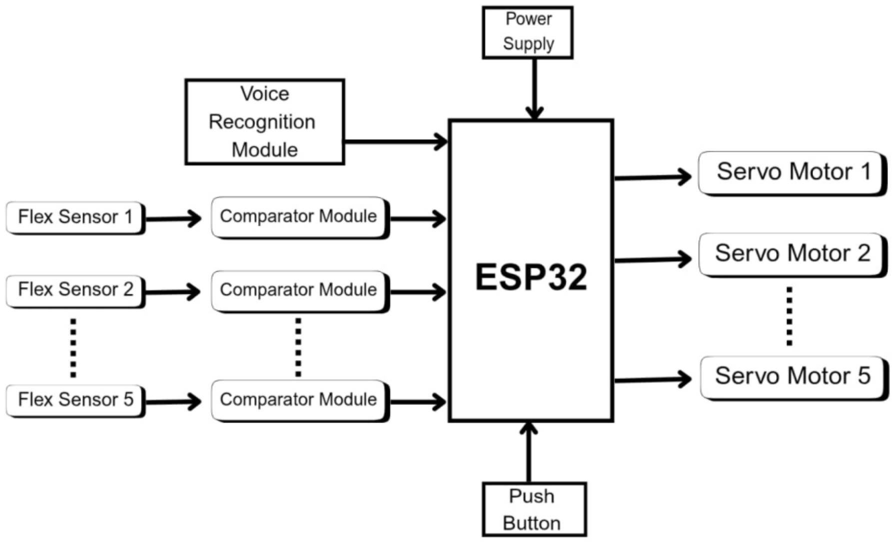

Fig. 1. Block diagram of the hybrid-controlled prosthetic finger system

III. MECHANICAL DESIGN

The mechanical structure of the prosthetic finger is inspired by the natural anatomy of a human finger. It consists of three main segments representing the proximal, middle, and distal phalanges. These segments are connected through hinge joints that allow smooth rotational movement. Instead of assigning a separate motor to each joint, the design follows an underactuated tendon-driven approach. A single tendon runs along the length of the finger and connects all three joints. When the servo motor rotates, it pulls the tendon, generating tension that causes the finger to bend in a coordinated sequence. The proximal joint flexes first, followed by the middle and distal joints. This sequential motion closely resembles the natural curling behavior of a human finger [1][4]. To ensure smooth return motion, elastic elements are incorporated into the structure. When the servo releases the tendon, these elastic components gently restore the finger to its extended position. This eliminates the need for an additional actuator for extension, further reducing system complexity [5]. The entire structure is fabricated using lightweight 3D printed material. This not only reduces the overall weight of the device but also allows easy customization of finger dimensions according to user requirements. Special attention was given to tendon routing and joint alignment to minimize friction and ensure consistent motion. By combining tendon-driven actuation with elastic return mechanisms, the mechanical design achieves a balance between simplicity and functional performance. The detailed CAD model of the proposed tendon-driven prosthetic finger is illustrated in Fig. 2.

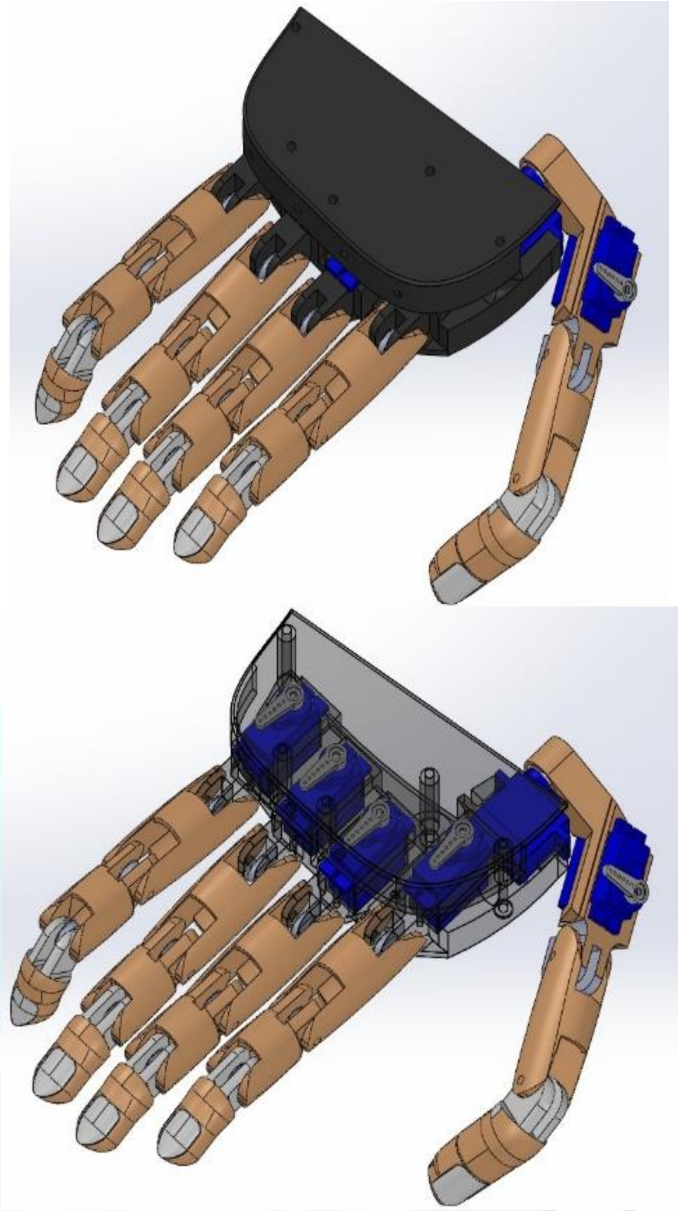

Fig. 2. Mechanical structure of the tendon-driven underactuated prosthetic finger

IV. CONTROL ARCHITECTURE

The control architecture of the proposed prosthetic finger is designed to achieve responsive, reliable, and user-friendly operation while maintaining overall system simplicity. Instead of relying on complex bio-signal acquisition systems, the architecture focuses on practical and accessible control methods that can be implemented using compact hardware. The system incorporates two independent yet complementary control modes: voice-based command input and gesture-based flex sensing. Both modes are centrally managed by the ESP32 microcontroller, which acts as the processing unit responsible for signal interpretation and actuation control. By integrating discrete voice commands with proportional gesture-based sensing, the architecture provides flexibility in operation and allows the user to interact with the prosthetic device in multiple intuitive ways. The dual-mode strategy enhances accessibility, adaptability, and ease of use without significantly increasing computational or hardware complexity [7].

4.1 Voice Control Interface

Voice integration enables hands-free operation of the prosthetic finger, making the system especially useful in situations where gesture-based control may not be practical. A dedicated voice recognition module is employed and trained with predefined commands such as “open” and “close.” When the user speaks a command, the module captures the acoustic signal and processes it internally using its built-in recognition algorithm. Upon successful identification of a trained keyword, the module generates a corresponding digital output signal. This output signal is transmitted to the ESP32 microcontroller through its digital input interface. The controller verifies the received command and maps it to a predefined servo position corresponding to either finger flexion or extension. Based on this mapping, the ESP32 generates a Pulse Width Modulation (PWM) signal with an appropriate duty cycle to control the servo motor. The servo motor then rotates to a specific angle, pulling or releasing the tendon connected to the finger mechanism. Voice control operates on discrete command-based logic, ensuring consistent and repeatable finger movement. Since the servo positions are predefined, the system provides stable actuation without requiring continuous feedback processing. This mode enhances accessibility for users with limited residual limb mobility [8] and offers a straightforward interaction method that does not require physical effort. Additionally, the voice-based approach demonstrates the feasibility of integrating simple human–machine interaction techniques into assistive prosthetic systems.

4.2 Gesture-Based Flex Control

While voice integration provides command-based operation, gesture-based control introduces proportional and real-time movement replication. A flex sensor is mounted on the user's healthy finger to capture natural bending motion. The sensor operates by varying its electrical resistance according to the degree of bending. As the finger bends, the resistance increases, leading to a measurable change in voltage when configured within a voltage divider circuit. The analog voltage signal generated by the flex sensor is continuously read by the ESP32 through its analog-to-digital conversion (ADC) interface. The controller processes this analog input and translates it into a corresponding PWM signal to drive the servo motor. Unlike voice control, which operates through fixed angles, gesture-based control allows dynamic and proportional adjustment of the servo position. As the user bends their finger further, the servo rotates accordingly, resulting in a mirrored and synchronized motion in the prosthetic finger. This proportional control mechanism enhances realism and provides smoother, more lifelike motion. It enables the prosthetic finger to adapt gradually to different grasping positions rather than switching between only fully open and fully closed states. During testing, this mode demonstrated improved user engagement and intuitive operation, as the movement felt more natural and responsive. By combining voice integration and flex-based gesture sensing within a unified microcontroller framework, the control architecture achieves a balance between simplicity and adaptability. The centralized ESP32 processing ensures efficient signal handling, while PWM-based actuation guarantees stable and controlled mechanical output. Overall, the architecture successfully bridges electronic signal processing with biomechanical actuation, enabling adaptive, smooth, and accessible prosthetic finger movement.

V. CIRCUIT CONFIGURATION AND IMPLEMENTATION

The electronic circuit of the proposed prosthetic finger integrates sensing, processing, and actuation within a compact and practical configuration. The ESP32-WROOM-32 development board serves as the central control unit, coordinating communication between the input modules and the servo actuators. The overall circuit is designed to ensure stable power delivery, reliable signal acquisition, and smooth motor control.

A regulated power supply section is implemented using a buck converter to provide a stable 5V output for the system components. This regulation is essential because servo motors draw varying currents during movement, which can otherwise lead to voltage fluctuations and unstable microcontroller operation. All modules share a common ground to maintain proper signal reference and system stability.

Flex sensors are interfaced with the ESP32 through signal conditioning modules. Each sensor operates by changing its resistance in response to bending. This resistance variation is converted into a corresponding voltage signal using a voltage divider configuration. The analog output is then read by the ESP32's analog-to-digital converter (ADC), allowing proportional interpretation of finger movement. This enables real-time gesture-based control of the prosthetic finger.

The voice recognition module is connected to the ESP32 through digital communication lines. When a predefined voice command is detected, the module transmits a corresponding digital signal to the controller. The ESP32 interprets this signal and maps it to a predefined motion command. This allows discrete control of finger opening and closing through spoken instructions.

Servo motors are connected to PWM-capable GPIO pins of the ESP32. The controller generates Pulse Width Modulation signals to precisely control the angular position of each servo. As the servo rotates, it actuates the tendon mechanism attached to the prosthetic finger, resulting in coordinated joint flexion.

Proper routing of power and signal lines ensures minimal electrical noise and consistent actuation performance.

The complete electronic configuration, as illustrated in Fig. 3, demonstrates the integration of dual input modules, centralized processing, and servo-based actuation within a unified system. The circuit design emphasizes simplicity, reliability, and ease of implementation while maintaining functional adaptability of the prosthetic finger.

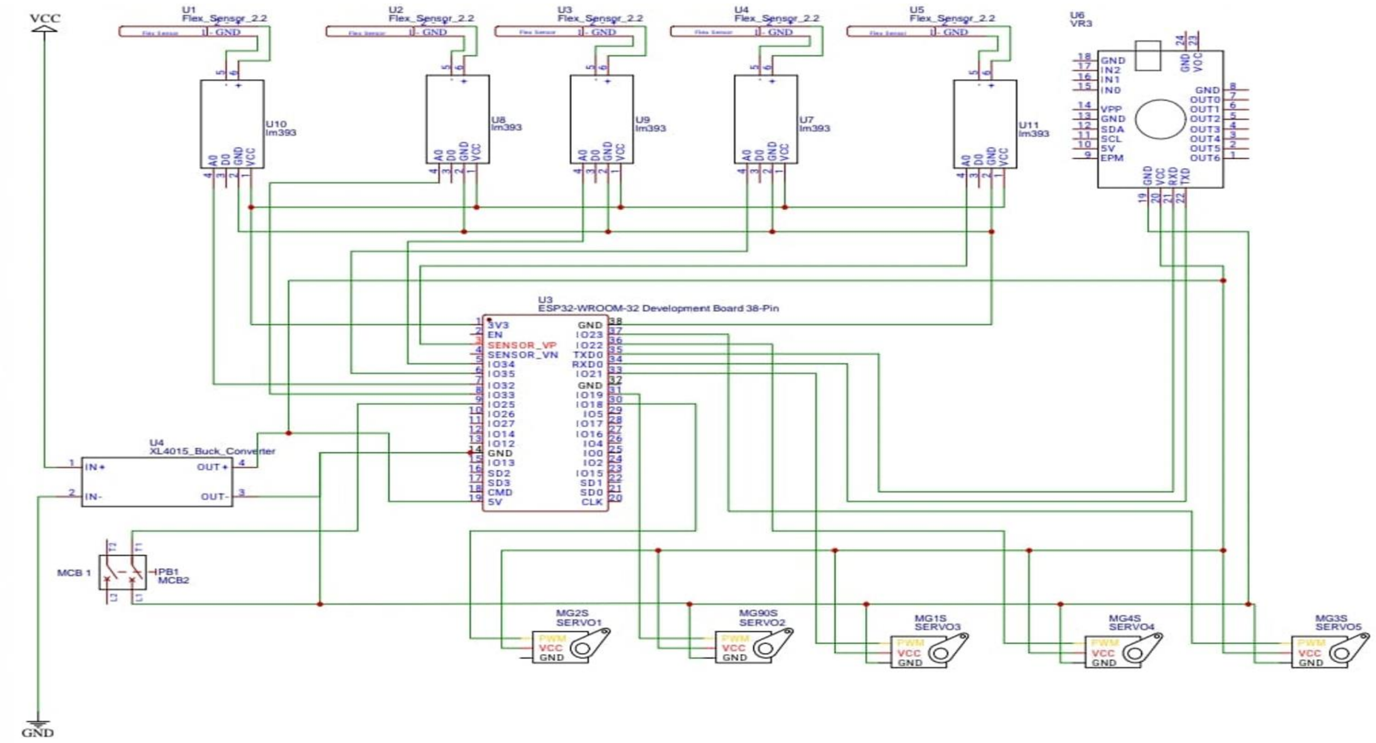

Fig. 3. Electronic circuit diagram of the hybrid-controlled prosthetic finger system

VI. HARDWARE IMPLEMENTATION

The hardware prototype was developed to validate the practical feasibility of the proposed hybrid-controlled prosthetic finger system. The implementation focused on achieving reliable integration between the sensing glove, control electronics, and the tendon-driven prosthetic mechanism while maintaining structural simplicity and operational stability.

The central control unit of the system is the ESP32 microcontroller, which coordinates input processing and motor actuation. The controller is mounted on a compact base along with supporting electronic components, including the voice recognition module, signal conditioning circuits for the flex sensors, and the regulated power supply unit. Careful wiring and proper grounding were ensured to minimize electrical noise and maintain consistent signal transmission.

A sensing glove is used to capture natural finger movements. Flex sensors embedded along the fingers detect bending motion by varying their electrical resistance. These variations are converted into corresponding voltage signals and transmitted to the ESP32 for processing. This configuration allows real-time gesture replication in the prosthetic hand.

For voice-based control, the voice recognition module is interfaced directly with the ESP32. When a predefined command is detected, the module sends a corresponding digital signal to the controller, enabling discrete control of finger motion. This dual-input setup allows both gesture-based proportional control and simple command-based operation.

The prosthetic hand itself is fabricated using lightweight 3D printed components. Each finger is actuated through a tendon-driven mechanism connected to servo motors mounted within the hand structure. As the servo rotates, it pulls the tendon, causing coordinated bending of the finger joints. Elastic elements integrated into the finger assembly provide passive extension when tension is released, eliminating the need for additional actuators.

During assembly, special attention was given to mechanical alignment, tendon routing, and servo mounting to ensure smooth and consistent motion. Power stability was carefully managed to prevent voltage fluctuations during motor operation, which is particularly important due to the variable current demand of servo motors.

The completed hardware prototype demonstrates successful integration of sensing, processing, and actuation modules. Testing confirmed stable servo response, accurate gesture mirroring, and reliable voice command execution. The physical realization of the system highlights the practicality of combining underactuated mechanical design with accessible electronic control to create a functional and cost-effective assistive device. The developed hardware prototype of the proposed prosthetic finger system is illustrated in Fig. 4.

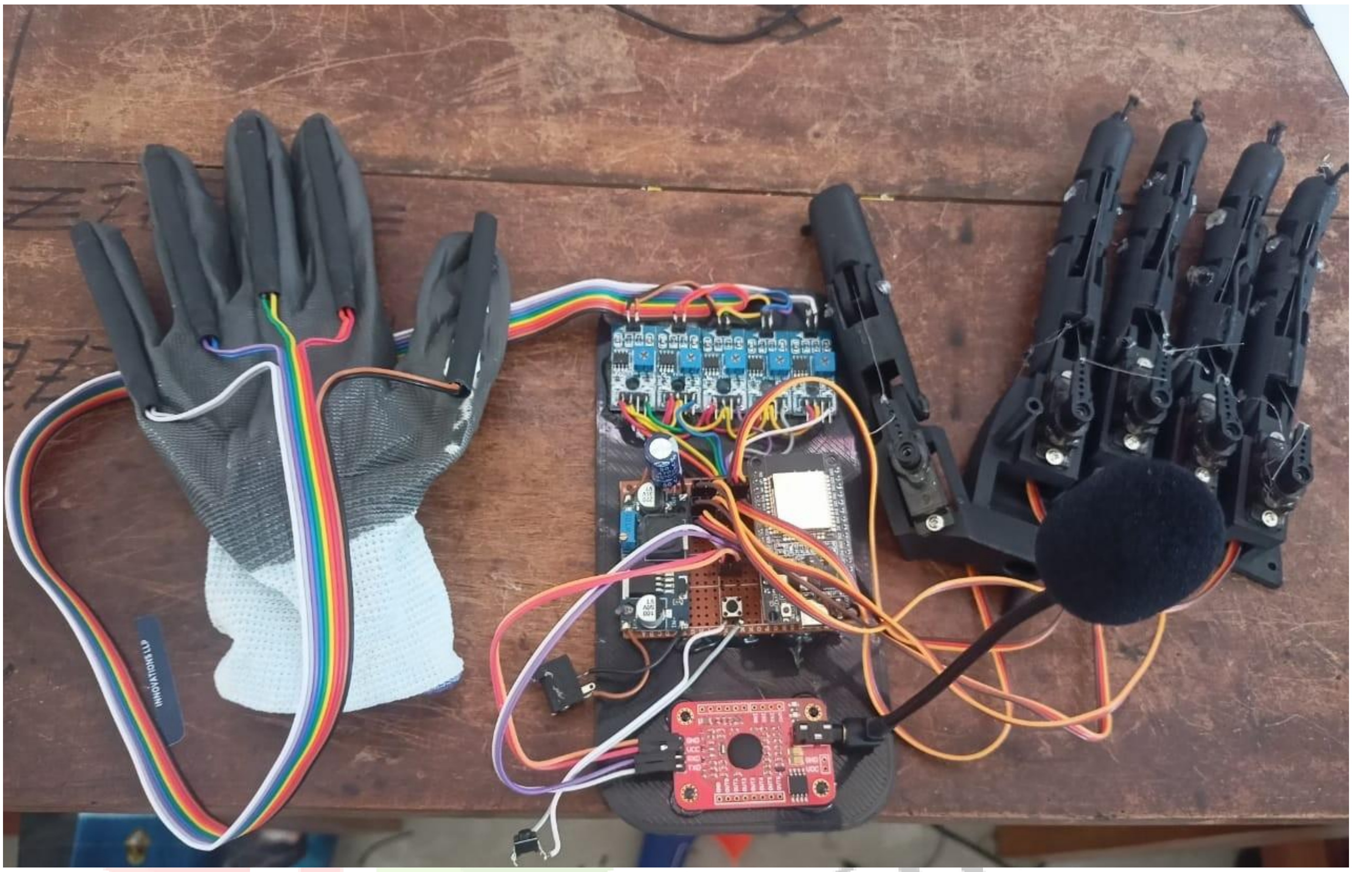

Fig. 4. Hardware prototype of the hybrid-controlled prosthetic finger system

VII. RESULT AND DISCUSSION

The developed hardware prototype was tested under both voice-controlled and gesture-based operating modes to evaluate its functional performance and overall system stability. During experimentation, the ESP32 microcontroller processed input signals reliably and generated consistent PWM outputs for servo actuation without noticeable delay. In voice-controlled mode, predefined commands such as “open” and “close” were recognized with satisfactory accuracy under normal indoor conditions, resulting in repeatable and stable finger motion; however, minor sensitivity to background noise indicated the importance of proper calibration and environmental control. In gesture-based mode, the flex sensors enabled proportional and real-time control of finger movement, allowing the prosthetic finger to mirror natural bending motion smoothly. The tendon-driven underactuated mechanism demonstrated coordinated sequential joint flexion using a single actuator, validating the mechanical efficiency of the design [1][6]. The elastic return elements ensured smooth extension when tension was released, further simplifying the actuation system [2][5]. Hardware evaluation also emphasized the need for stable power regulation and proper tendon alignment to avoid servo fluctuation and motion inconsistencies. Overall, the results confirm that the proposed hybrid-controlled prosthetic finger achieves reliable actuation, intuitive control, and mechanical adaptability within a compact and cost-effective framework, demonstrating its practical feasibility for assistive applications.

VIII. CONCLUSION

This work presented the design, development, and hardware implementation of a hybrid-controlled underactuated prosthetic finger that integrates biomechanical simplicity with intuitive control strategies. The proposed system adopts a tendon-driven mechanism to achieve coordinated multi-joint motion using a reduced number of actuators, thereby minimizing mechanical complexity, power consumption, and structural weight. By leveraging underactuation principles, the finger is capable of producing adaptive and sequential joint flexion, closely resembling natural human finger movement while maintaining structural efficiency. In addition to mechanical optimization, the integration of dual control modes—voice-based commands and gesture-based flex sensing—enhances the usability and accessibility of the system. Voice control enables discrete and hands-free operation, while gesture-based sensing provides proportional and real-time motion replication. The centralized ESP32 microcontroller successfully coordinates sensing, processing, and actuation, ensuring stable PWM control and reliable servo performance. Hardware testing demonstrated smooth tendon-driven motion, consistent response under both control modes, and effective integration of electronic and mechanical components. The developed prototype confirms that it is possible to balance affordability, adaptability, and functional performance within a compact prosthetic system. By combining biomimetic mechanical design with accessible embedded control techniques, the proposed prosthetic finger provides a practical and scalable foundation for assistive hand rehabilitation and daily-use applications. The outcomes of this work demonstrate the feasibility of implementing cost-effective, user-friendly prosthetic solutions without relying on highly complex or expensive actuation systems.

IX. FUTURE SCOPE

Although the proposed hybrid-controlled underactuated prosthetic finger demonstrates practical feasibility and functional adaptability, several improvements can be explored in future work. One important extension would be the integration of electromyography (EMG) signals to enable direct muscle-based control, thereby enhancing natural interaction and reducing dependency on external input devices. The implementation of wireless communication modules and mobile application interfaces could further improve portability and user convenience. Additionally, the current single-finger actuation concept can be expanded into a fully articulated multi-finger prosthetic hand with coordinated grasp patterns. Advanced signal processing techniques and machine learning algorithms may also be incorporated to improve gesture recognition accuracy and adaptive control behavior. Finally, clinical testing and user feedback studies would provide valuable insights into ergonomics, comfort, and long-term usability, contributing to the refinement and real-world deployment of the system.

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