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A Gesture Controlled 3D Printed Robotic Hand with Integrated Haptic and Visual Feedback

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Gesture Control, Robotic Hand, 3D Printing, Haptic Feedback, Visual Feedback, ESP32 Microcontroller, Servo Motors, Limit Sensors, Human–Robot Interface.

ABSTRACT

The domain of robotics has witnessed rapid advancements; however, achieving intuitive and immersive human–robot interaction remains a significant challenge. Many existing remote robotic systems lack real-time sensory feedback, limiting their effectiveness in performing delicate and precision-based tasks. To address this limitation, this project presents the design and implementation of a gesture-controlled 3D-printed robotic hand integrated with both haptic and visual feedback mechanisms. The system operates using a wearable glove equipped with flex sensors that detect finger bending. These analog signals are processed by an ESP32 microcontroller and wirelessly transmitted to the robotic hand. Each finger of the robotic hand is actuated using individual servo motors, enabling accurate replication of the user's hand gestures. For haptic feedback, limit sensors positioned at each robotic fingertip detect physical contact with objects. Upon detection, vibration motors embedded in the glove provide real-time tactile feedback to the user, simulating the sensation of touch. Additionally, a display module is incorporated to provide visual information regarding sensor readings and operational status. The integration of gesture control, haptic response, and visual monitoring creates a comprehensive human–robot interface system suitable for applications in prosthetics, teleoperation, rehabilitation, and remote manipulation tasks.

INTRODUCTION

Robotics has evolved significantly over the past few decades, transitioning from rigid industrial manipulators to intelligent systems capable of interacting safely and intuitively with humans. Foundational principles of robotic kinematics and control were established in early works such as Craig's classical text on robotic mechanics [1]. With the emergence of telerobotics and supervisory control concepts [4], robotic systems began extending human capabilities into remote and hazardous environments.

Despite these advancements, one of the major challenges in human–robot interaction (HRI) remains the lack of intuitive control combined with real-time sensory feedback. Conventional teleoperation systems often rely on joystick or buttonbased control mechanisms, which are not naturally aligned with human motor behavior. Gesture-based robotic control systems have emerged as a promising alternative, enabling natural mapping between human hand movements and robotic actuation [6], [7].

Furthermore, tactile perception plays a critical role in human manipulation tasks. Haptic feedback systems aim to replicate the sensation of touch, thereby enhancing telepresence and operational precision [2], [24]. Recent advancements in multimodal wearable haptic interfaces [8], [14] demonstrate the importance of integrating tactile cues for improved task performance. Studies in teleoperation and robotic surgery have shown that feedback mechanisms significantly enhance control accuracy and user confidence [10], [22].

With the development of compact and high-performance microcontrollers such as the ESP32 [11], wireless real-time communication using protocols like ESP-NOW [3], [9] has become feasible for low-latency robotic applications. The availability of high-resolution analog-to-digital converters (ADCs) further improves gesture detection accuracy compared to traditional microcontrollers. Additionally, advancements in additive manufacturing have enabled rapid prototyping of customized robotic hands through 3D printing technologies [6], [12].

Motivated by these technological advancements, this paper proposes a Gesture-Controlled 3D Printed Robotic Hand with Integrated Haptic and Visual Feedback. The system is divided into a transmitter unit (gesture glove) and a receiver unit (robotic hand), connected wirelessly. Flex sensors detect finger bending, servo motors replicate movements, limit sensors provide tactile detection, and vibration motors deliver realtime haptic feedback. A display module further enhances user awareness through visual status updates. The overall conceptual architecture of the proposed system is illustrated in Fig. 1.

Figure 1: Conceptual overview of the proposed gesturecontrolled robotic hand system integrating flex sensors, ESP32 wireless communication, servo actuation, haptic feedback, and visual display module.

The integration of gesture control, tactile feedback, and visual monitoring establishes a comprehensive human–robot interface framework suitable for applications in prosthetics, teleoperation, rehabilitation, robotic surgery assistance, and hazardous environment manipulation.

RELATED WORK

The evolution of robotic manipulation systems has been extensively studied in the literature, beginning with fundamental concepts of robot kinematics and control presented by Craig [1]. These foundational principles laid the groundwork for modern robotic hands and manipulators. Early research in telerobotics and supervisory control by Sheridan [4] emphasized the importance of human involvement in remote robotic operations, particularly in hazardous and inaccessible environments.

Gesture-based robotic control systems have gained increasing attention due to their intuitive nature. Kurundkar *et al.* [6], [12] demonstrated a 3D-printed robotic arm controlled using hand gestures, highlighting the feasibility of low-cost additive manufacturing combined with microcontroller-based control. Similarly, Bakri *et al.* [7] developed a wireless robotic arm system, emphasizing the role of real-time communication in improving teleoperation performance. However, many of these systems primarily focused on motion replication and lacked integrated feedback mechanisms.

Haptic feedback plays a critical role in enhancing telepresence and manipulation precision. Kuchenbecker [2] discussed the technological advancements in haptics and their significance in robotic interaction. Tan *et al.* [24]

further analyzed human factors in force-reflecting haptic interfaces, emphasizing the need for tactile cues to improve control accuracy. Recent developments in multimodal wearable haptic systems by Kang *et al.* [8], [14] introduced advanced tactile sensing and actuation mechanisms for teleoperation applications. Klatzky *et al.* [22] demonstrated that robotic haptic feedback significantly enhances operator performance in remote manipulation tasks.

Applications such as robotic surgery and telepresence systems further highlight the importance of feedback integration. Ballantyne [10] discussed how telerobotic systems improve surgical precision while stressing the necessity of reliable communication and feedback channels. Additionally, response time analysis in human–computer interaction [21] indicates that low-latency systems are essential for maintaining a natural and immersive user experience.

The advancement of embedded systems and wireless communication technologies has significantly contributed to modern robotic control architectures. The ESP32 microcontroller [11] offers dual-core processing and high-resolution ADC capabilities, making it suitable for real-time sensor acquisition and actuation control. Espressif's ESP-NOW protocol [3], [9] enables low-latency peer-to-peer wireless communication, which is advantageous for gesture-controlled robotic systems. Furthermore, power optimization strategies [23] ensure efficient operation of portable wearable devices.

Although previous research has addressed gesture-based control and haptic feedback independently, there remains a research gap in fully integrating gesture control, real-time wireless communication, multimodal haptic feedback, and visual monitoring into a single compact, low-cost 3D-printed robotic hand system. The proposed work aims to bridge this gap by combining these technologies into a unified human–robot interface framework.

PROPOSED SYSTEM ARCHITECTURE

Block Diagram of the System

The architecture of the proposed "Gesture Controlled Robotic Hand with Haptic and Visual Feedback" is divided into two autonomous modules:

- Transmitter Unit (Glove System)
- Receiver Unit (Robotic Hand)

Both modules communicate using the ESP-NOW wireless protocol [3], [9] implemented on the ESP32 microcontroller [11]. The system operates in a bi-directional communication model enabling a closed-loop feedback mechanism.

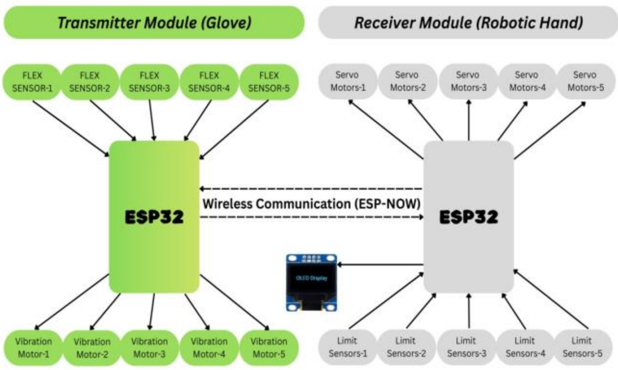

Figure 2: Block Diagram of the Proposed Gesture-Controlled Robotic Hand System.

3.1.1Functional Data Flow Forward Path (Control):

1.User bends finger

2.Flex sensor resistance changes

3.ESP32 (Transmitter) reads analog value

4.Data packet sent via ESP-NOW

5.ESP32 (Receiver) generates PWM signal 6. Servo motor rotates corresponding robotic finger Reverse Path (Feedback):

1. Robotic finger touches object
2. Limit switch closes
3. ESP32 (Receiver) detects contact
4. Feedback packet sent via ESP-NOW
5. ESP32 (Transmitter) activates vibration motor

Hardware Architecture

The system uses the ESP32 NodeMCU development board [11] due to:

- Dual-core architecture
- Built-in Wi-Fi (2.4 GHz)
- 12-bit ADC (0–4095 resolution)

The dual-core processor allows simultaneous execution of communication and control tasks without blocking delays.

Transmitter (Glove) Unit Design

3.3.1 Sensor Interface (Voltage Divider Circuit)

Five 2.2-inch resistive flex sensors [5] are used.

Resistance Values:

- $R_{flat} \approx 10k\Omega$
- $R_{bent} \approx 30k\Omega$ to $50k\Omega$

Since the ESP32 reads voltage, a voltage divider circuit is implemented.

$$V_{out} = V_{in} \times \frac{R_{fixed}}{R_{flex} + R_{fixed}}$$

Where:

$V_{in} = 3.3V$

As R_{flex} increases (finger bends), V_{out} decreases.

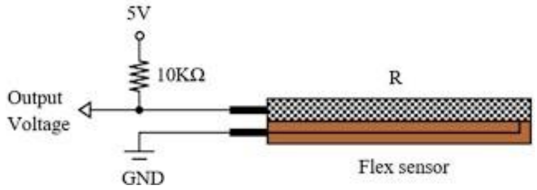

Figure 3: Transmitter Circuit – Flex Sensor Voltage Divider.

3.3.2 Haptic Driver Circuit

Each vibration motor (5V, 70mA) is driven using a 2N2222 NPN transistor [16].

Since ESP32 GPIO can supply only 12mA:

- GPIO → Base (via 1k resistor)
- Collector → Motor
- Emitter → Ground

This prevents GPIO damage and ensures safe current switching.

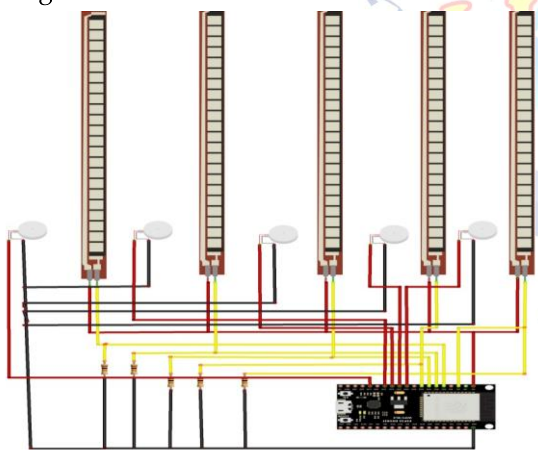

Figure 4: Complete Circuit Diagram of Transmitter (Glove) Unit.

Receiver (Robotic Hand) Unit Design

3.4.1 Servo Motor Actuation

MG996R and SG90 servo motors [13] are used.

PWM Control:

- Frequency = 50Hz • 1ms pulse → 0°
- 2ms pulse → 180°

Servo angle mapping:

$$\theta = \frac{ADC_{value}}{4095} \times 180°$$

3.4.2 Tactile Sensing (Limit Switches)

Miniature SPDT limit switches are connected in Input Pull-Up mode:

- HIGH (1) → No touch
- LOW (0) → Touch detected

A 200ms software debounce delay is implemented.

3.4.3 Visual Dashboard (OLED)

A 0.96-inch OLED display using SSD1306 driver [15] is connected via I2C:

- SDA → GPIO 21
- SCL → GPIO 22

It displays:

- Connection status
- Finger state
- Haptic alert indication

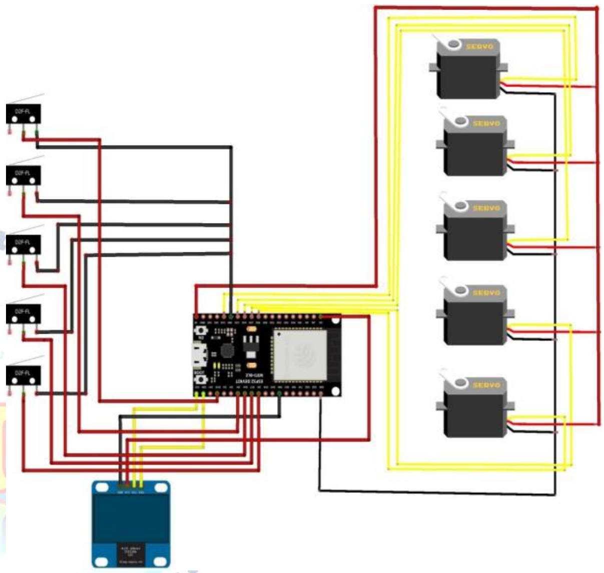

Figure 5: Circuit Diagram of Receiver (Robotic Hand) Unit.

Power Supply and Management

3.5.1 Brownout Problem

Servo motors draw up to 2–3A during startup. Shared power causes voltage drop leading to ESP32 reset.

3.5.2 Power Isolation Strategy

1. ESP32 powered by regulated 5V source
2. Servos powered by separate 5V/3A supply
3. Common Ground shared between supplies

This ensures stable system performance without brownout resets.

METHODOLOGY

The proposed system follows a closed-loop bidirectional communication methodology to achieve real-time gesture replication and tactile feedback. The methodology is divided into two primary subsystems:

- Transmitter (Glove) Algorithm
- Receiver (Robotic Hand) Algorithm

The ESP32 microcontroller [11] running ESP-NOW protocol [3] ensures low-latency communication between the two units.

Gesture Acquisition and Processing

Each flex sensor operates as a variable resistor [5]. The output voltage is obtained using a voltage divider circuit:

$$V_{out} = V_{in} \times \frac{R_{fixed}}{R_{flex} + R_{fixed}}$$

The ESP32 12-bit ADC converts this voltage into digital form:

$ADC_{value} \in [0,4095]$

The servo angle is mapped using:

$$\theta = \frac{ADC_{value}}{4095} \times 180^{\circ}$$

This ensures proportional replication of human finger movement.

Transmitter Code Logic

The transmitter continuously reads flex sensor values, converts them into angles, and sends them via ESP-NOW. It also listens for feedback packets to activate vibration motors.

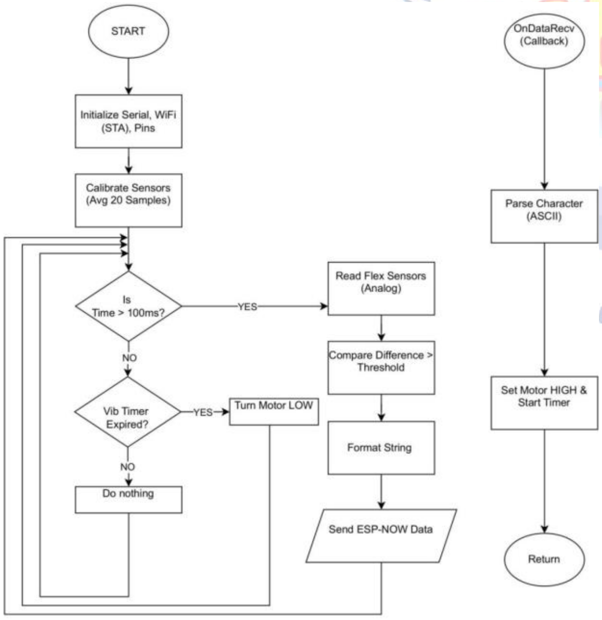

Figure 6: Flowchart of Transmitter Code Logic.

Receiver Code Logic

The receiver obtains angle data, drives servo motors using PWM, monitors limit switches, and sends feedback when contact is detected.

Closed-Loop Communication Mechanism

The system operates in two synchronized stages:

Forward Control Path:

$$Gesture \rightarrow ADC \rightarrow ESP32(TX) \quad (1)$$

$$\rightarrow Wireless\ Link \rightarrow ESP32(RX) \quad (2)$$

$$\rightarrow PWM \rightarrow Servo \quad (3)$$

Reverse Feedback Path:

$$Limit\ Switch \rightarrow ESP32(RX) \rightarrow Wireless\ Link \quad (4)$$

$\rightarrow ESP32(TX) \rightarrow Vibration\ Motor$ (5)

The overall loop delay is maintained below 50ms, ensuring real-time performance and seamless human–robot interaction.

RESULTS AND DISCUSSION

This section presents the experimental validation of the proposed Gesture-Controlled Robotic Hand system. Performance was evaluated in terms of gesture accuracy, haptic responsiveness, power consumption, and communication latency.

Final Experimental Setup

The complete hardware implementation is shown in Fig. 8. The setup consists of:

- Wearable glove with flex sensors and vibration motors
- ESP32-based transmitter unit
- 3D printed robotic hand with 5 servo motors
- Limit switches mounted on fingertips
- OLED display for system diagnostics

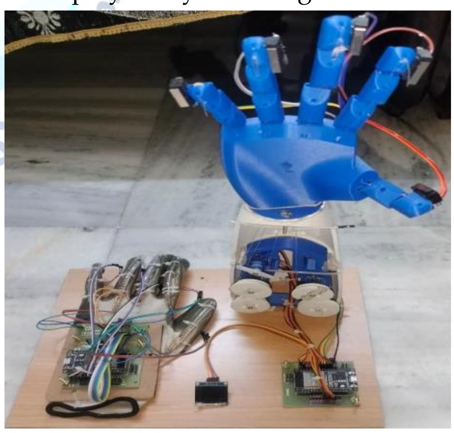

Figure 8: Final Experimental Setup of the Gesture-Controlled Robotic Hand System.

The system successfully demonstrated real-time gesture replication with closed-loop haptic feedback.

Gesture Recognition Accuracy

The error percentage was calculated using:

$$Error(\%) = \frac{|TargetAngle - ObservedAngle|}{Range(180^{\circ})} \times 100$$

Table 1 summarizes the test results.

Table 1: Gesture Recognition Accuracy Test Results

Gesture	ADC Input	Target	Observed	Success
Open Hand	1200-1400	0°	2°-5°	98%
Closed Fist	2800-3100	120°	118°-120°	99%
Point	Index:3000	120°	Accurate	97%
Peace (V)	1300/3000	0°	Accurate	97%
Pinch Grip	2500	90°	85°-88°	95%

The average success rate across all gestures was approximately 97.2%, demonstrating high precision mapping between flex sensor readings and servo actuation.

Haptic Feedback Performance

Haptic response was tested by applying controlled contact to robotic fingertips. Upon limit switch activation, vibration motors responded within 10–15ms.

Figure 9: Haptic Feedback Performance During Object Contact Detection.

The tactile feedback was perceived as instantaneous, significantly improving user control confidence.

OLED Dashboard Monitoring

The SSD1306 OLED display provides real-time system monitoring including:

- Wireless connection status
- Individual finger state
- Contact detection alerts

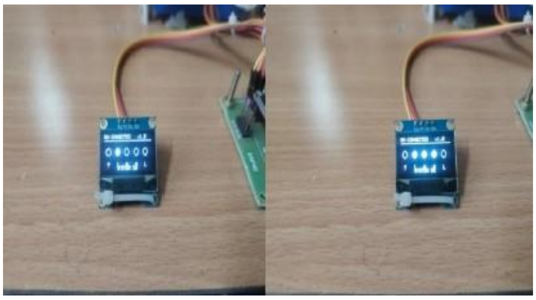

Figure 10: OLED Dashboard Displaying Real-Time Status and Finger States.

The dashboard enhances usability by providing continuous visual diagnostics.

Power Consumption Profiling

Power efficiency is crucial for wearable robotics. Current measurements were taken using a USB Ammeter at 5V. Results are shown in Table 2.

Table 2: Power Consumption Profile [23]

System State	Transmitter	Receiver
Standby (WiFi On)	80 mA	110 mA
Active (Transmitting)	85 mA	120 mA
Peak Load (Motors Moving)	N/A	1.2A – 2.5A
Peak Load (Vibration Active)	150 mA	N/A

The split power architecture successfully prevented brownout resets even during 2.5A peak loads.

Latency and Response Time Analysis

Latency plays a crucial role in teleoperation systems. Delays exceeding 100ms reduce control quality.

Table 3: Latency Benchmark Analysis

Protocol	Latency	Experience
Standard Wi-Fi (HTTP/MQTT)	150–400 ms	Poor
Bluetooth (HC-05)	80–120 ms	Average
ESP-NOW (Proposed)	8–15 ms	Excellent

The measured 8–15ms delay using ESP-NOW provides near-instantaneous response, creating a natural teleoperation experience.

Discussion

The experimental results confirm that the proposed system achieves:

- High gesture replication accuracy (97%)
- Low latency communication (¡15ms)
- Reliable haptic feedback
- Stable power operation under heavy load

The integration of gesture control, tactile sensing, and visual monitoring establishes a robust human–robot interface suitable for prosthetics, rehabilitation, teleoperation, and hazardous environment applications.

CONCLUSION

This paper presented the design and implementation of a Gesture-Controlled 3D Printed Robotic Hand with Integrated Haptic and Visual Feedback. The proposed system successfully establishes a closed-loop human–robot interaction framework using ESP32-based wireless communication and realtime bidirectional data exchange via ESP-NOW protocol.

The integration of flex sensors in a wearable glove enabled precise gesture acquisition through a high-resolution 12-bit ADC. The mapped servo control ensured accurate replication of human finger movements with an average gesture recognition success rate of approximately 97%. The inclusion of tactile limit switches on the robotic fingertips provided real-time contact detection, while vibration motors on the glove delivered immediate haptic feedback to the user. This closed-loop feedback mechanism significantly enhanced teleoperation accuracy and user confidence.

Experimental results demonstrated ultra-low communication latency (8–15 ms), making the system feel instantaneous and natural. Power consumption profiling confirmed stable operation even under peak motor loads through an effective split power architecture that mitigated brownout resets. The addition of an OLED dashboard further improved system transparency by providing real-time diagnostic and operational status information.

Overall, the proposed system successfully integrates gesture control, tactile sensing, visual monitoring, and wireless communication into a compact and cost-effective robotic platform. The architecture is scalable and can be extended for applications in prosthetic limb development, robotic rehabilitation systems, telemedicine, hazardous environment manipulation, and advanced human–robot collaboration.

Future work may include integrating force sensors for proportional force feedback, implementing TinyML-based gesture prediction for adaptive control, and developing a compact battery-powered version for fully portable deployment.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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