

Design and Implementation of a Hand Gesture–Based Wireless Control System for Lamp and Fan Appliances

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ABSTRACT

This paper reports the design and implementation of a contactless, hand gesture–based wireless control interface for basic household appliances. A PAJ7620 gesture recognition sensor, integrated with a transmitter ESP32, detects four predefined gestures and sends control commands via ESP-NOW to a receiver ESP32. The receiver actuates a lamp indicator (LED) and a 5 V DC fan through a relay module. Custom PCBs and 3D-printed enclosures were developed to improve integration and portability. Functional testing verified correct gesture-to-actuation mapping, stable device-to-device communication, and state retention between commands. The proposed approach reduces reliance on touch and speech input, making it suitable for noisy environments and for users who benefit from contactless interaction in home and care settings.

Keywords: Hand Gesture Control, PAJ7620, ESP32, Contactless Switching, Assistive Technology

INTRODUCTION

Smart home technologies are increasingly used to improve convenience and automation, and they can also support accessibility for older adults and individuals with disabilities (Fakhimi et al., 2025; Mun et al., 2025). For users with reduced hand function, even simple tasks such as switching a light or fan may affect independence and daily quality of life (Aktar et al., 2024; Fakhimi et al., 2025).

Current smart home interfaces commonly rely on voice commands or mobile applications (Iliev & Ilieva, 2022). Voice control uses Natural Language Processing (NLP) to interpret spoken input (Iliev & Ilieva, 2022; Zhou et al., 2020), but performance may degrade in noisy environments and commands may be misinterpreted (Vanus et al., 2015). Mobile applications offer flexible monitoring and device control, yet they require physical interaction with a smartphone and may introduce usability barriers for some users (Amouzadeh et al., 2025; De Oliveira et al., 2022; Sung et al., 2019).

To address these limitations, this study develops a contactless hand gesture-controlled lamp and fan system. A PAJ7620 gesture recognition sensor detects predefined hand movements, which are processed by an ESP32-

based controller and transmitted via ESP-NOW. This direct device-to-device communication enables local operation without router or internet connectivity, supporting simple and responsive appliance control.

Gesture-based appliance control has been widely explored using both vision-based and dedicated sensor-based approaches. For example, Wang et al. (2021) demonstrated a gesture-based smart home control prototype using an embedded controller and relays to operate multiple household devices, while Jose et al. (2025) reported a bedside gesture interface for controlling a light and fan using an ESP32 and a gesture sensor to improve hygiene in care settings. More recent work has also used camera-based hand tracking and machine learning to achieve higher gesture vocabulary and quantified accuracy, at the expense of increased computational complexity (Hobbs & Ali, 2025; Yang et al., 2023). In contrast, the present work focuses on a low-cost, low-computation implementation using a dedicated IR gesture sensor and ESP-NOW for router-free wireless command delivery, and provides a complete end-to-end build including PCB fabrication and enclosure integration.

The scope of this study is limited to contactless control of two appliances (lamp and fan) using four gestures (right, left, clockwise circle, and counterclockwise circle), with local wireless communication implemented through ESP-NOW. Evaluation is based on functional tests that verify correct detection, transmission, and output switching.

This work contributes a low-cost, sensor-based human-machine interface (HMI) for appliance control that avoids speech input and reduces the need for physical contact, with potential relevance to accessibility- and hygiene-focused environments.

METHODOLOGY

This section describes the development process of the hand gesture-controlled smart lamp and fan system, from initial planning to prototype fabrication and testing. The methodology covers the project workflow, system architecture, software and hardware implementation, PCB fabrication, prototype assembly, and operating procedure.

Project Overview

The project was executed in four structured stages (refer to the project flowchart in Figure 1):

- i) Stage 1 - Literature survey: Relevant studies, component datasheets, and prior designs were reviewed to define system requirements, select suitable hardware, and determine feasible gesture-to-action mapping. Guidance from the supervisor was used to validate technical decisions and resolve design constraints.
- ii) Stage 2 - Circuit testing (simulation and breadboard validation): Circuit connections and control logic were first verified using schematic design tools and then validated using physical wiring. The microcontroller firmware was developed and iteratively debugged to ensure stable gesture detection, reliable wireless transmission, and correct actuator switching.
- iii) Stage 3 - PCB design and fabrication: After the circuit operated reliably on a breadboard, PCB schematics and layouts were designed. The boards were fabricated and assembled in the laboratory, followed by continuity checking and functional verification before integration into the prototype housing.
- iv) Stage 4 - Prototype development and integration: The transmitter and receiver modules were packaged into prototype enclosures (3D-printed). Final system testing was conducted to confirm end-to-end operation under normal usage conditions.

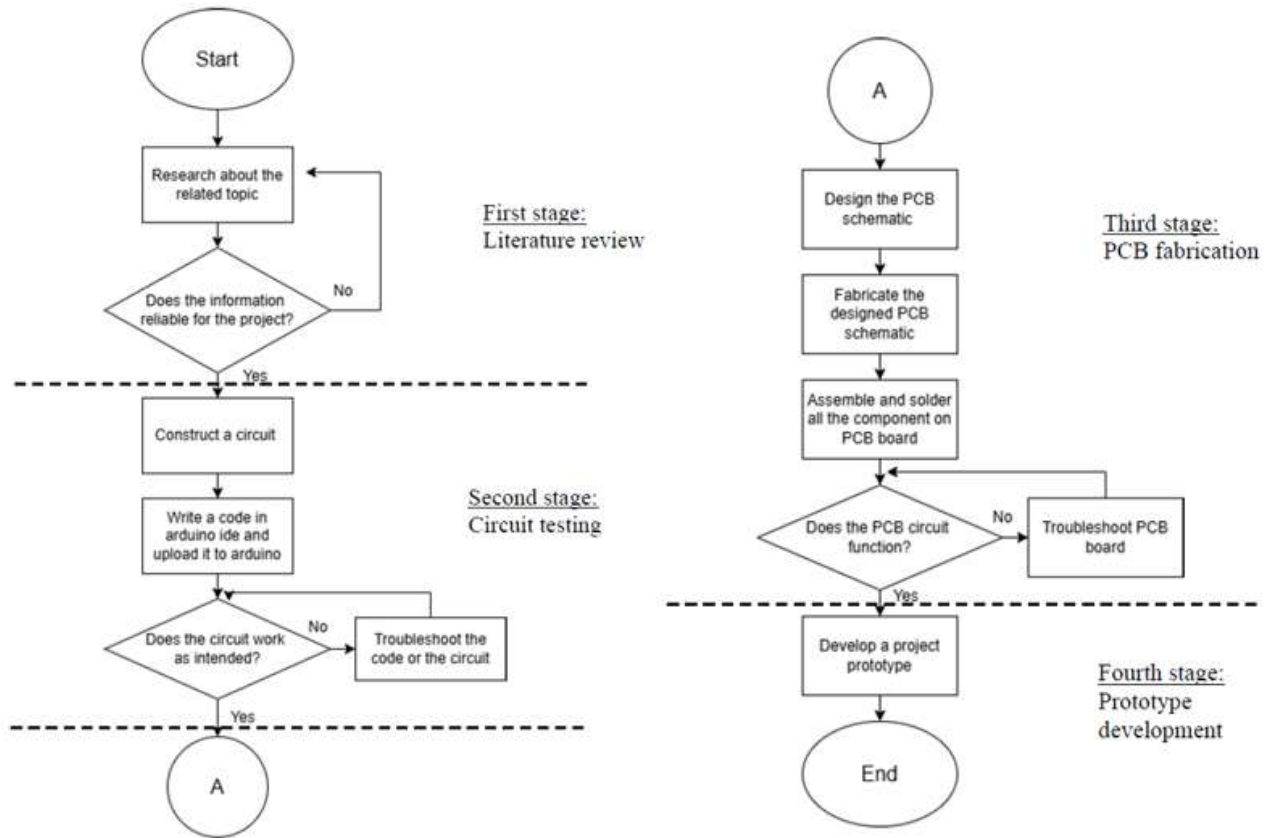


Figure 1: Project Flowchart Showing the Four Stages

System Architecture and Operating Principle

Figure 2 presents the overall block diagram of the proposed system.

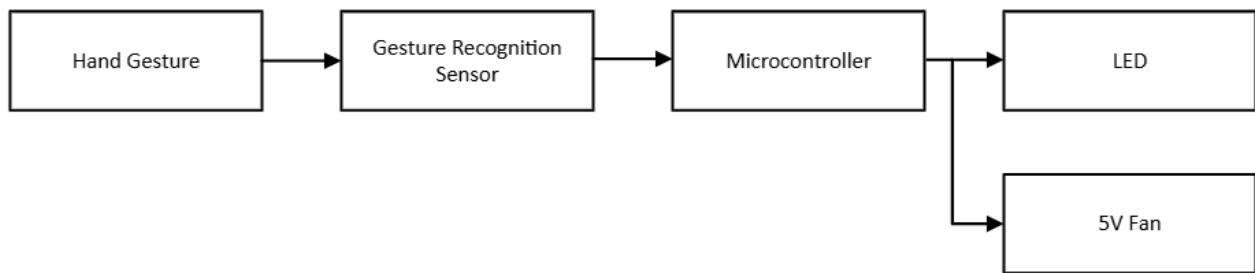


Figure 2: Block Diagram of the Hand Gesture-Controlled System

The design consists of two main modules:

i) Transmitter module (gesture input unit)

- Input sensor: PAJ7620 gesture recognition sensor
- Controller: ESP32 (NodeMCU)
- Function: Detects predefined hand gestures and converts them into control commands.

- **Communication:** Sends commands wirelessly to the receiver using ESP-NOW, enabling direct device-to-device communication without router or internet connectivity.
- ii) Receiver module (appliance control unit)
- **Controller:** ESP32 (NodeMCU)
 - **Outputs:** Red LED (lamp indicator), 5 V DC motor (fan) controlled through a relay module
 - **Function:** Receives commands from the transmitter and switches the corresponding output ON/OFF.

Although the PAJ7620 can support multiple gesture types (PixArt Imaging Inc., 2016), this project uses four gestures for simple and repeatable control. Table 1 summarizes the command mapping.

Table 1: Gesture Input and System Output

Gesture Input	Output Action
Right wave	Turn ON LED (lamp)
Left wave	Turn OFF LED (lamp)
Circle clockwise	Turn ON DC motor (fan)
Circle counter clockwise	Turn OFF DC motor (fan)

Default behavior: If no gesture is detected, the system maintains the previous output state until a new command is received.

Software

(A) Fritzing (schematic documentation)

Fritzing was used to draft and document the transmitter and receiver schematics prior to hardware assembly. It supports clear visualization of wiring and component connections and allows importing custom part libraries when needed. The completed transmitter and receiver schematics are shown in Figure 3 and Figure 4.

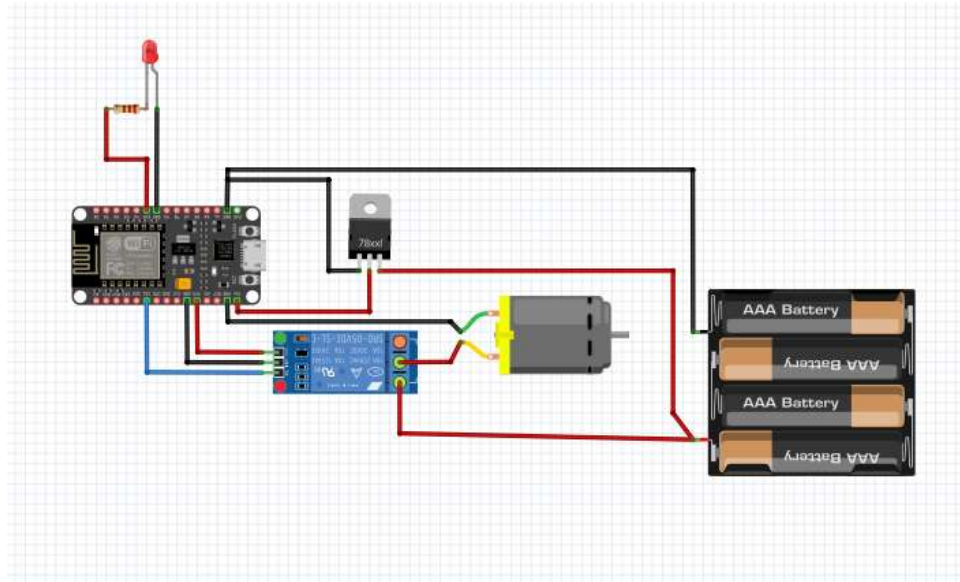


Figure Error! No text of specified style in document.: Receiver Circuit Diagram for the Hand Gesture-Controlled Smart Lamp and Fan System

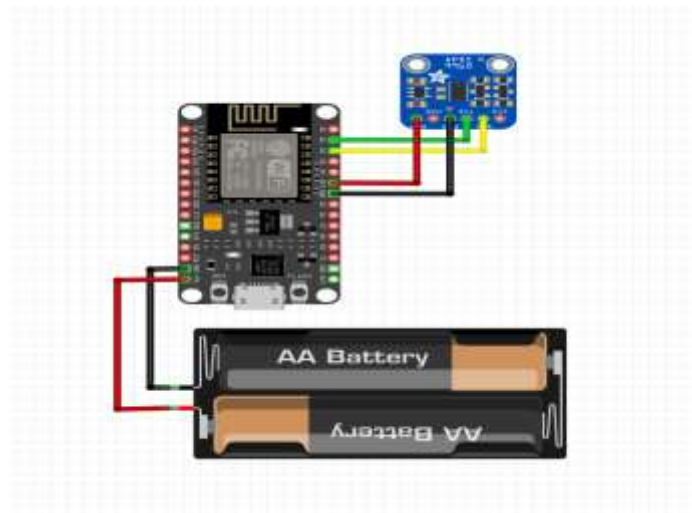


Figure 4: Transmitter Circuit Diagram for the Hand Gesture-Controlled Smart Lamp and Fan System

(B) Arduino IDE (firmware development)

Arduino IDE was used to develop, compile, and upload firmware to the ESP32 boards. The program includes routines for:

- PAJ7620 initialization and gesture reading (I²C communication)
- Command encoding/decoding
- ESP-NOW transmitter/receiver configuration
- Output control logic for LED and relay switching

(C) EasyEDA (PCB schematic and layout)

EasyEDA was used to design the PCB schematics and layouts for both modules. The design process followed these steps:

1. Create schematic circuits for transmitter and receiver

2. Assign footprints and verify pin mapping
3. Convert schematic to PCB layout
4. Route traces (manual/assisted routing) and adjust design rules (trace width, clearances, hole sizes)
5. Export layout for fabrication

(D) Blender (3D enclosure design)

Blender was used to design the transmitter and receiver enclosures for 3D printing. The enclosure geometry was developed to support mounting, cable routing, and visibility of outputs.

Hardware

(A) ESP32 (NodeMCU) microcontroller

ESP32 boards were used in both transmitter and receiver modules due to their processing capability and built-in wireless features. One ESP32 handles gesture sensing and transmission, while the second receives commands and switches the outputs.

(B) PAJ7620 gesture recognition sensor

The PAJ7620 integrates gesture recognition with an I²C interface and includes an IR emitter and optics, enabling gesture detection within short-range operating distances (PixArt Imaging Inc., 2016). In this project, the sensor is mounted in the transmitter enclosure facing outward to detect user gestures.

(C) LED and current-limiting resistor

A red LED represents the lamp output. A 220 Ω resistor is connected in series to limit current and prevent LED damage.

(D) DC motor (fan) and relay module

A 5 V DC motor is used as the fan load. Since the motor requires higher current than the ESP32 GPIO can supply, a 5 V relay module is used as an electrical interface, enabling safe switching of the motor supply using low-power control signals.

(E) Power supply

A 4×AA battery pack provides supply power for the prototype. Power is distributed to the ESP32 and relay/motor circuit through the appropriate input pins and wiring, ensuring stable operation during demonstrations.

Printed Circuit Board (PCB) Fabrication

PCB fabrication was conducted in the laboratory based on the finalized EasyEDA layout. The main steps were:

- i) Artwork printing: PCB layout was printed onto a transparent film.
- ii) UV exposure: The film was aligned on the photoresist board and exposed using a UV exposure machine.
- iii) Developing: The exposed board was developed until the copper pattern became visible. (Safety: PPE such as gloves, apron, and mask were used to handle chemicals.)
- iv) Etching: Unprotected copper was removed using the etching process until only the intended copper traces remained.

- v) Resist stripping: Remaining photoresist was removed to reveal clean copper tracks.
- vi) Cleaning, drying, and drilling: The board was washed, dried, drilled at component holes, and cut to final size.
- vii) Inspection and assembly: Continuity testing using a multimeter was performed before soldering components. Final functional testing verified correct operation of each board prior to enclosure installation.

This fabrication process follows standard PCB production principles (K. Mitzner, 2009).

Prototype Development and Integration

Two enclosures were produced: one for the transmitter and one for the receiver (Figure 5). The transmitter enclosure includes an opening/window to allow IR transmission and gesture sensing. The receiver enclosure includes openings for the motor output and LED placement to make system operation visually observable.

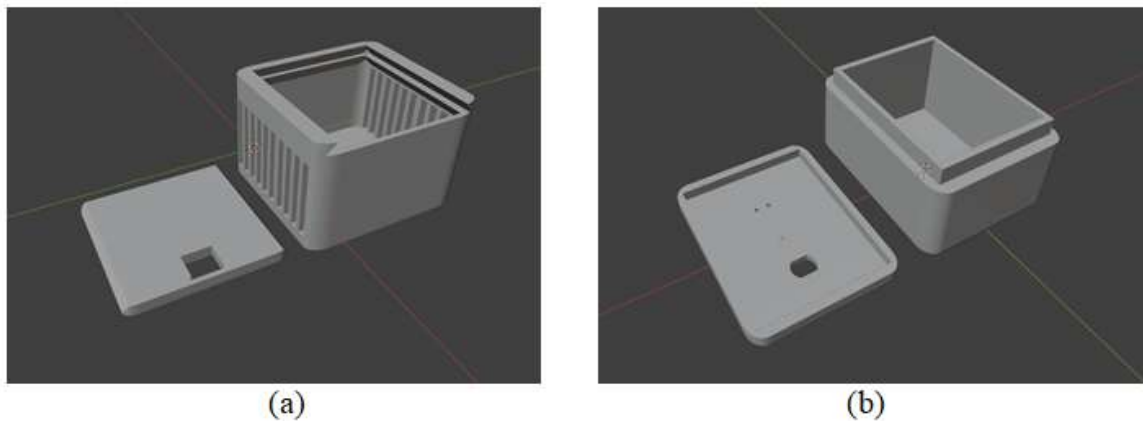


Figure 5: 3D Enclosure Designs: (a) Transmitter Prototype, and (b) Receiver Prototype

Both enclosures were fabricated using a 3D printer (Figure 6). After printing:

- PCBs were mounted securely inside the enclosures
- Wiring was arranged for safe routing and minimal strain
- Final end-to-end testing confirmed wireless command transmission and correct output switching



Figure 6: Bambu A1 Mini 3D Printer Used for Prototype Fabrication

Operating Procedure (User Guide)

The system is operated using the following steps:

1. The PAJ7620 sensor is mounted on the transmitter module facing the user.
2. The transmitter ESP32 reads the gesture and converts it into a command.
3. The command is sent wirelessly (ESP-NOW) to the receiver ESP32.
4. The receiver switches outputs based on the gesture mapping:
 - Right wave → LED ON
 - Left wave → LED OFF
 - Clockwise circle → Motor ON
 - Counterclockwise circle → Motor OFF
5. If no gesture is detected, the previous output state remains unchanged until a new gesture command is received.

RESULTS AND DISCUSSION

This section presents the outcomes of the hand gesture-controlled smart lamp and fan system and discusses the final prototype performance and operation. The discussion focuses on system functionality, prototype implementation (PCB and enclosure), observations during functional testing, and limitations encountered during development. The section also highlights the relevance to contactless interaction and accessibility.

(A) Prototype Overview

The proposed system enables users to control two basic appliances; lamp and fan - using predefined hand gestures without physical contact. Compared with conventional wall switches, the prototype provides a touch-free interface that can support users who face challenges operating physical switches. Unlike voice-based control, the system is not affected by background noise and does not rely on speech input.

In addition, compared with vision-based gesture control systems that use cameras and machine learning, the proposed approach is simpler, lower-cost, and easier to implement. Camera-based solutions typically require a more powerful processor, higher energy consumption, and training data to achieve reliable recognition. In

contrast, this project uses a dedicated gesture sensor (PAJ7620) that provides direct gesture recognition with minimal computational burden, enabling real-time operation on an ESP32 microcontroller. The wireless link (ESP-NOW) further improves usability by allowing flexible placement and device-to-device communication without internet connectivity.

(B) Prototype Results and Functionality

(i) PCB Implementation

The final hardware implementation consists of two modules: a transmitter PCB and a receiver PCB. The transmitter PCB integrates the PAJ7620 gesture sensor and an ESP32 microcontroller that reads gesture inputs and transmits commands. The receiver PCB contains an ESP32 microcontroller that receives the command and controls the outputs (LED and DC motor fan).

The transmitter and receiver PCBs were assembled and verified through continuity checks and functional testing. Figure 7 - Figure 8 show the top and bottom views of both boards after fabrication and soldering. Overall, the PCB-based implementation improved wiring reliability and reduced loose connections compared to breadboard construction, resulting in a more stable final prototype.

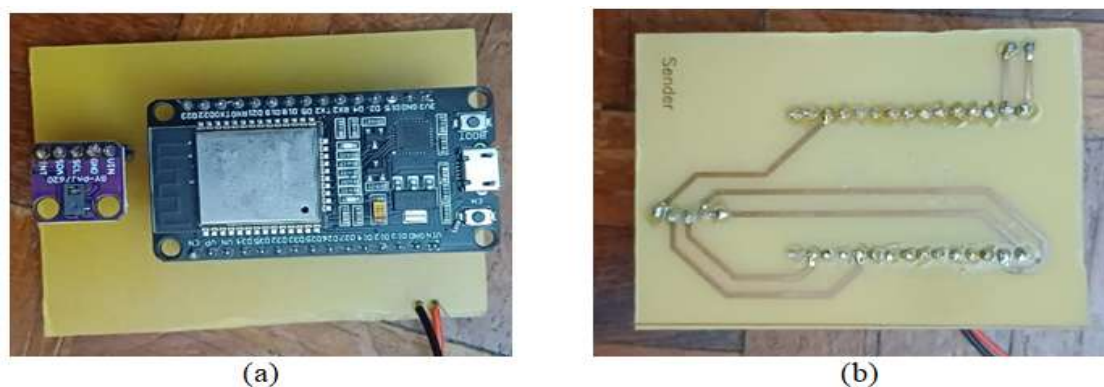


Figure 7: Transmitter PCB Board Views: (a) Top View, and (b) Bottom View

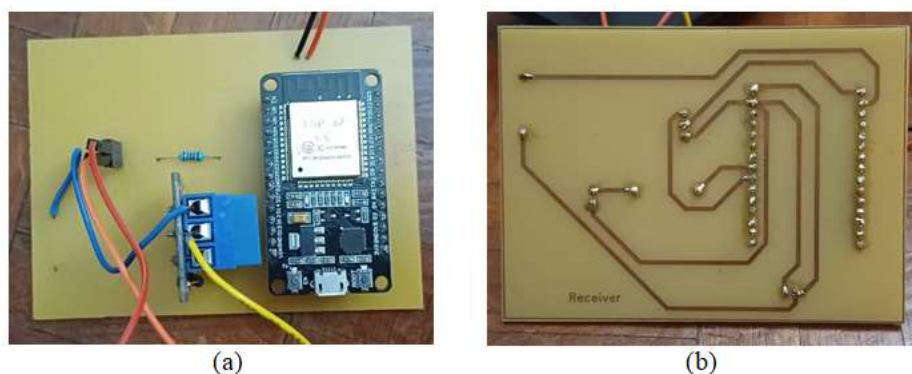


Figure 8: Receiver PCB Board Views: (a) Top View, and (b) Bottom View

(ii) Prototype Integration (Enclosure and Assembly)

After validating the PCB circuits, both modules were integrated into 3D-printed enclosures. The transmitter enclosure was designed with an opening to allow infrared (IR) transmission and ensure the gesture sensor can detect hand movement. The receiver enclosure was designed to highlight the output indicators, including a mount for the motor and visible placement for the LED pins to allow clear observation during demonstration.

Figure 9 - Figure 10 show the overall and internal views of both the transmitter and receiver prototypes. The use of a 3D-printed casing improved user handling, protected the electronics, and enhanced the presentation quality of the final system.



Figure 9: Transmitter Prototype Views: (a) Overall View, and (b) Internal View

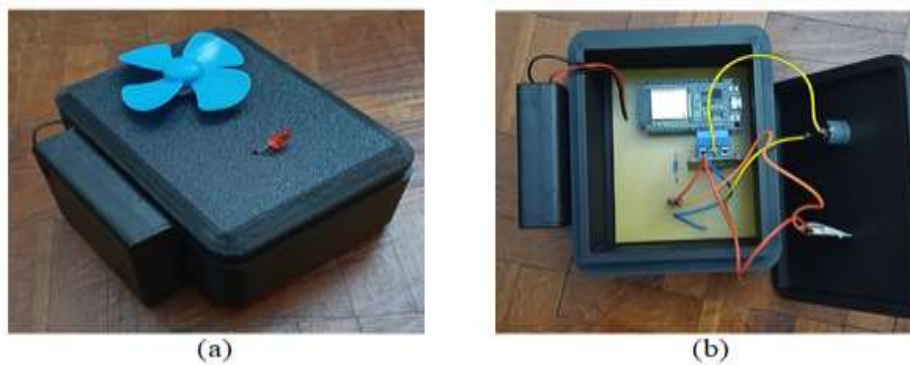


Figure 10: Receiver Prototype Views: (a) Overall View, and (b) Internal View

(iii) Functional Testing and Output Response

Functional testing was conducted to verify the correct gesture-to-output mapping and confirm stable wireless operation between modules. The default system condition is OFF for both outputs (shown in Figure 11). When no gesture is detected, the output state remains unchanged until a valid new command is received.



Figure 11: Initial State of the Hand Gesture-Controlled Smart Lamp and Fan System (LED and Fan OFF)

The system was tested using four predefined gestures as described in Table 1.

- (a) Lamp (LED) control: For lamp control, a right wave gesture turns ON the LED (shown in Figure 12). A left wave gesture turns OFF the LED (shown in Figure 13).



Figure 12: Lamp Control Using Right Wave Gesture: (a) Right Wave Gesture, and (b) LED ON



Figure 13: Lamp Control Using Left Wave Gesture: (a) Left Wave Gesture, and (b) LED OFF

- (b) Fan (DC motor) control: A clockwise circular gesture turns ON the DC motor fan (shown in Figure 14). A counterclockwise circular gesture turns OFF the DC motor fan (shown in Figure 15).

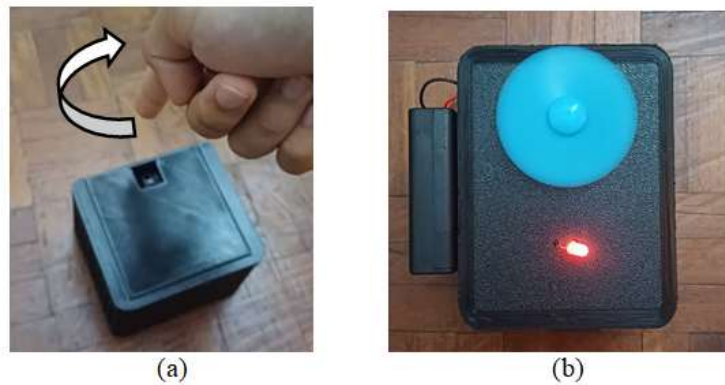


Figure 14: Fan Control Using Circular Gestures: (a) Clockwise Circular Gesture, and (b) DC Motor Fan ON

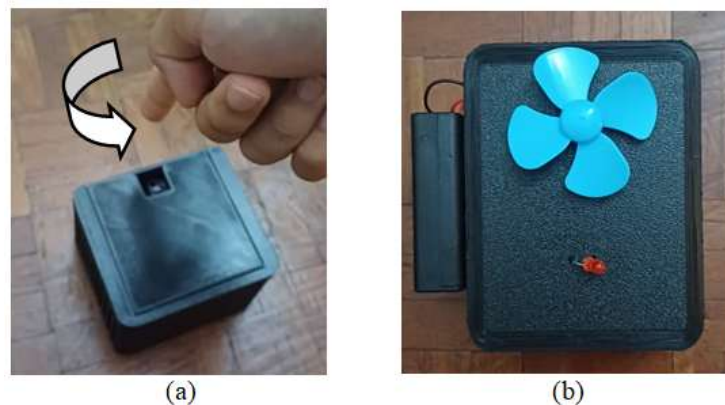


Figure 15: Fan Control Using Circular Gestures: (a) Counterclockwise Circular Gesture, and (b) DC Motor Fan OFF

During testing, the system consistently executed commands after detecting a valid gesture input. The appliance states were maintained until the opposite gesture command was issued, ensuring predictable user control (e.g., LED remains ON until a left wave is detected). This behaviour is useful for real use cases because it prevents unintended switching due to brief sensor interruptions.

Planned Performance Evaluation Protocol

Quantitative performance evaluation was not recorded during the current prototype demonstration; therefore, no numerical accuracy or response-time results are reported in this version. To enable reproducible assessment in future work, three recommended metrics are defined: (i) gesture recognition accuracy, (ii) end-to-end command success rate, and (iii) response time. Accuracy can be computed as the percentage of correctly recognised gestures over repeated trials. End-to-end success can be defined as correct output switching at the receiver following a valid gesture. Response time can be measured as the elapsed time between gesture detection at the transmitter and the corresponding output state change at the receiver, captured using timestamp logging in the ESP32 firmware. Table 2 summarises a suggested test matrix across hand-sensor distances and ambient lighting conditions consistent with the operating range of the PAJ7620 sensor.

Table 2: Suggested Test Matrix for Quantitative Performance Evaluation (To Be Conducted in Future Work)

Test condition	Distance (cm)	Lighting condition	Trials per gesture (n)	Gestures tested	Metrics recorded
Near range test	10	Indoor (normal)	20	R, L, CW, CCW	Accuracy (%), success rate (%), response time (ms)
Far range test	20	Indoor (normal)	20	R, L, CW, CCW	Accuracy (%), success rate (%), response time (ms)
Far limit test	30	Indoor (normal)	20	R, L, CW, CCW	Accuracy (%), success rate (%), response time (ms)
Low-light robustness	20	Low light	20	R, L, CW, CCW	Accuracy (%), success rate (%), response time (ms)
Bright-light robustness	20	Bright light / sunlight	20	R, L, CW, CCW	Accuracy (%), success rate (%), response time (ms)
False-trigger check	20	Indoor (normal)	-	No gesture / random motion	False trigger count; debouncing effectiveness

Planned Usability Evaluation

A usability study was not conducted during the current prototype demonstration; therefore, participant-based usability outcomes are not reported in this version. To support future validation in assistive and domestic contexts, a short questionnaire is proposed to capture perceived ease of use, learnability, and overall satisfaction. Participants can interact with the prototype and rate each statement on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree). Table 3 lists recommended survey items, and Table 4 provides a suggested reporting format for summarising results.

Table 3: Proposed Usability Survey Items (5-Point Likert Scale)

Item	Statement
U1	The system was easy to learn.

U2	The gestures were easy to remember.
U3	The system responded quickly to my gestures.
U4	The contactless interaction is useful for my daily routine or work setting.
U5	Overall, I am satisfied with the system.

Table 4: Suggested Reporting Format for Usability Survey Results (To Be Completed in Future Work)

Statistic	U1	U2	U3	U4	U5	Overall
Mean (1–5)						
Std. dev. (1–5)						

Comparison with Related Work

To contextualise the contribution, Table 5 compares the proposed prototype with representative gesture-based appliance control systems reported in the literature. Compared to vision-based approaches, the proposed design uses a dedicated IR gesture sensor to reduce computational load, and uses ESP-NOW for direct device-to-device communication without internet connectivity.

Table 5: Comparison with Related Gesture-Based Appliance Control Systems

Study	Sensing method	Controller / Communication	Appliances	Gestures	Reported evaluation
This work	PAJ7620 IR gesture sensor	ESP32 / ESP-NOW	Lamp (LED), 5V fan	4	Functional demo; evaluation protocol (Table 2 – Table 4)
Wang et al. (2021)	Gesture sensor + IR transmitter	Arduino Mega / IR + relays	Multiple home devices	Multiple	Prototype demonstration (smart home control)
Omweno et al. (2023)	Voice + gesture sensor	Arduino / wireless (Bluetooth)	DC motor fan	Multiple	Functional operation reported
Hobbs & Ali (2025)	Camera + hand landmark ML	Raspberry Pi 5 / local	Multiple GPIO devices	Discrete set	Quantified accuracy and frame rate
Jose et al. (2025)	APDS-9960 gesture sensor	ESP32 / relays	Light, fan, emergency alert	4	Prototype demonstration for bedside control

(C) Discussion, Limitations, and Future Work

During development, the initial gesture sensor (APDS-9960) showed inconsistent behaviour when interfaced with the ESP32 platform, including unreliable gesture detection at short distances. After troubleshooting, the sensor module was replaced with the PAJ7620, which provided more consistent recognition and supported a wider gesture vocabulary. This hardware change improved stability of the final prototype.

Despite successful functional operation, several limitations should be noted. First, the PAJ7620 recognition performance depends on operating range and environmental conditions. According to the datasheet, gesture detection is specified for near (approximately 5–15 cm) and far (approximately 15–30 cm) modes, and may be affected by ambient infrared sources and reflective backgrounds (PixArt Imaging Inc., 2016). Second, false triggering may occur if non-gesture motion enters the sensor field-of-view; therefore, practical deployments should include input debouncing, confirmation logic, or user feedback to minimise unintended switching. Third,

the current prototype is limited to two appliances and four gestures; however, scalability can be achieved by extending the command structure (e.g., device addressing), adding additional receiver nodes, and supporting a larger gesture set for mode selection. For real household deployment, switching of mains-voltage appliances should be implemented using appropriately rated relay/triac modules with electrical isolation (e.g., opto-isolated drivers) and enclosure safety measures. Integration with existing smart home platforms (e.g., MQTT/Home Assistant) is also feasible by bridging ESP-NOW commands to Wi-Fi networks via a gateway node (Espressif Systems, n.d.).

(D) Environmental and Sustainability Considerations

Although the work is presented as a prototype for appliance control, contactless interaction can contribute to broader sustainability and social goals by supporting safer, more inclusive living environments and reducing reliance on disposable interfaces in shared spaces.

- i) SDG 9 (Industry, Innovation and Infrastructure): The proposed gesture-based interface demonstrates a low-cost, embedded sensing and communication solution that can support accessible and user-centered appliance control using widely available components.
- ii) SDG 11 (Sustainable Cities and Communities): The prototype supports safer and more inclusive living environments by enabling contactless appliance control. In shared spaces and care settings, reducing surface contact may lower hygiene risks and support independent operation for users with limited mobility.

CONCLUSIONS

This paper presented a hand gesture-based wireless control system that enables contactless switching of a lamp indicator and a 5 V DC fan using a PAJ7620 gesture sensor, ESP32 controllers, and ESP-NOW device-to-device communication. Functional demonstrations confirmed correct gesture-to-output mapping, stable command delivery between transmitter and receiver modules, and predictable state retention between commands. Although quantitative performance and participant-based usability results were not recorded in the current prototype demonstration, the manuscript provides suggested protocols and reporting formats (Table 2 – Table 4) to guide future evaluation of recognition accuracy, end-to-end success rate, response time, and user-perceived usability. Overall, the proposed architecture provides a low-cost contactless interface that can complement existing smart home control methods, particularly in settings where reduced touch interaction and simple operation are priorities.

Future work will focus on completing and reporting the full quantitative trial set across distances and lighting conditions, extending the design to additional appliances, and implementing isolated switching hardware suitable for mains-voltage loads.

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