

# Gesture Recognition Using TinyML Model Implementation On Low Cost Microcontroller For Appliance Control

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**Abstract**— Gesture Control Systems provide a contactless control mechanism of electrical appliances in smart homes which is intuitive. The current paper introduces a low-cost gesture recognition system that is carried out with the ESP32-CAM microcontroller and a simplistic TinyML-based vision system. When the system is launched, all hardware equipment, such as the camera, relay modules, LCD display, and wireless network is initialized to make sure that it works reliably. The ESP32-CAM will constantly take real-time images of hands and send them to an edge-processing unit, which loads a hand landmark detection model based on MediaPipes. Images that have been captured are preprocessed by ensuring that they are resized and normalized to increase resistance to different illumination conditions. Hand landmarks are extracted into whether there are valid gestures or not and the system classifies the gestures that are recognized whilst ignoring those frames that do not have much significance to reduce false activations. Known gestures are also assigned to a set of control commands and sent back to the ESP32-CAM over Wi-Fi. The microcontroller uses relay modules to switch on and off lights and fans among other appliances, and also to display gesture and appliance status on 16×2 LCD. The operational loop makes it possible to have real-time, reliable, and energy-efficient gesture-based control of appliances, which proves that it is possible to deploy TinyML-assisted vision systems on resource-restricted, low-cost hardware platform.

**Keywords** — *Gesture Recognition, TinyML, ESP32-CAM, MediaPipe, Hand Landmark Detection, Smart Home Automation, Relay-Based Appliance Control, Edge Computing, Low-Cost Embedded System etc.,*

## I. INTRODUCTION

The sheer development of Internet of Things (IoT) technologies has changed conventional home settings to smart and intelligent homes to a great extent. A system of automating the house is supposed to improve the comfort, energy consumption, and security of the household members, allowing them to manage household appliances remotely and intelligently. These systems find reduced use especially with the aged and physically or sensually challenged individuals since they minimize the reliance on hand operated switches and physical contact with equipment [1]. Currently, the automation and accessibility of conventional home automation solutions are mainly based on the mobile application, voice recognition, or sensor-based interface. The voice automated system of home automation has received a lot of focus because of its hands-free

functionality and convenience [2], [3], [5]. Using these systems, users can manage appliances by commanding them straight by talking using microcontrollers like Arduino and NodeMCU. Nonetheless, voice-based interaction is very sensitive to the environment, accent, and speech impairment that in practice can severely limit the performance of the system in real-life situations [2], [9]. Also, voice processing based on the clouds generates latency and privacy issues [4], which restricts their applicability in real-time and applications with low power. In order to overcome these difficulties, some researches have looked into alternative control interfaces, such as smartphone-based interfaces, Bluetooth-supported systems and biometric authentication systems [7], [8], [11]- [15]. Although these methods enhance security and localized control, it still involves physical interaction or close proximity which might not be convenient to everybody. Besides, high-performance platforms like Raspberry Pi and cloud-based AI frameworks raise the cost of the system, power usage, and computational overhead [10], which is less practicable in large-scale systems or low-cost systems. The current developments of embedded artificial intelligence and Tiny Machine Learning (TinyML) have also made it possible to deploy smart

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models to resource-constrained devices. TinyML supports inference on-the-edge with very low latency and power usage, and superior privacy. Gesture recognition based on vision has become a prospective alternative to the natural human-machine interaction that allows controlling without speaking or using any physical control devices and operating intuitively without touching. Nevertheless, real-time gesture recognition on inexpensive microcontrollers remains only a feasibility study since it has low memory and processing power. This paper was inspired by these constraints, which will present a low-cost, TinyML-based gesture recognition system deployed on an ESP32-CAM microcontroller as a real-time appliance controller. The suggested system spreads intensive tasks of the computationally-intensive vision processing to an edge-processing unit without sacrificing the low-latency communication and the relay-based appliance control. Through the means of combining hand landmark detection, lightweight gesture classification, and IoT-based actuation, the system can be considered a sensible, contactless, and power-saving device to automate smart homes, which, in particular, can make life easier for people with disabilities and senior citizens.

## II. RELATED WORKS

Wireless Dr. P. Anuradha et al. introduced an IoT-based home automation system that was intended to support people with various disabilities to lead normal lives. The system incorporates IoT sensors, connectivity to the cloud, and mobile interfaces to help users to remotely operate household appliances. The work also goes a long way in enhancing availability and accessibility in smart homes, but mostly depends on conventional control systems like mobile apps and switches, without involving modern contactless approaches like gesture or vision-based control. Therefore, it can be used only in limited cases that demand to be hands free. [1]. Babit Geo Baby et al. created a voice activated home automation to support individuals with disabilities by allowing them to control appliances without using their hands by speaking. The system is more convenient and easier to use given the fact that physical contact with switches is eliminated. Nevertheless, ambient noise, pronunciation differences and speech disability affect the accuracy and reliability of the system considerably and may cause misuse of commands in real-world scenarios. [2]. Usman Isah Ibrahim et al. have described the design of a voice-controlled home

automation system based on Arduino microcontroller. The platform is seen to have a low-pricing and easy process of managing simple appliances in the house with the usage of voice order. This system, despite being simple, has no intelligent processing capabilities and does not offer any advanced methods of human-machine interaction like gesture recognition or human machine interaction based on machine learning. [3]. A smart home automation system is suggested by Vijaya Bhasker Reddy et al. as a combination of Internet of Things and the Artificial Intelligence technology. It allows making smart decisions, monitoring remotely, and making automation more effective. Nevertheless, this dependence on cloud-based AI processing opens up the possibility of latency, new network reliance, and more power usage, rendering it less viable in real-time and low-power embedded systems. [4]. Inam Ullah Khan et al. developed a home control automation system that is voice-controlled and based on its affordability and simplicity. The system enables the user to use spoken commands in order to operate appliances and this is an elementary form of automation. However, the system has a weakness of scalability and robustness especially in dealing with multiple appliances at the same time and also adapting them to various user environments. [5]. Vaibhav Malav et al. introduced a research study on the Arduino based home automation systems with low-cost implementation and easy deployment. The paper presents different automation methods through sensors and microcontrollers. Nevertheless, intelligent perception-based control approaches and real-time decision-making based on machine learning models are not studied. [6]. Abiodun E. Amoran et al. designed a home automation device based on the Android application and Bluetooth communication. The system allows to control local appliances without connecting to the internet, which improves the level of reliability in the setting with low network levels. Nevertheless, Bluetooth lacks remote accessibility due to the low communication range and it does not have provision of intelligent or adaptive control. [7]. Deepali Javale et al. proposed home automation and security system based on Android ADK. The system combines the control on mobile-based ground as well as the simplest security measures, which give centralized control of the appliances. The system, even though being very efficient, is based on the smartphone communication and does not integrate other contactless control systems like gestures or vision-based interfaces. [8]. Sonali Sen et al. came up

with an intelligent voice-controlled home automation system that enhances the efficiency of interaction by improving speech processing methods. The system is also more effective in command recognition than simple voice-controlled systems. Nonetheless, like other voice-based systems, it has a weakness to noise interference and cannot be used by users with speech disabilities. [9]. Bhaumik Vaidya et al. created an automation of the smart home system that has a special door monitoring system among the elderly users using Python, OpenCV, Android, and Raspberry Pi. The system improves the monitoring and safety using computer vision. The high-end hardware is effective but makes the system more expensive and consumes more power, so it is not easily applicable to low-cost embedded systems. [10]. Agung Triayudi suggested a fingerprint attendance system based on IoT and implemented with NodeMCU ESP8266 microcontroller. This system shows that it has a secure and reliable biometric authentication to access attendance. Nonetheless, it is application-oriented and does not deal with home automation or the multimodal interaction methodologies. [11]. Ritam Dutta et al. used Arduino UNO and GSM alert mechanism to implement a fingerprint-based system of attendance. The system offers access control that is secure and in real time. Although it is an effective method of biometric authentication, intelligent automation and applications in appliance control are not discussed in the work. [12]. Ramjee Prasad Gupta and Swati introduced a domotics system with biometric security on a smartphone. The system boosts the security of homes by use of biometric authentication. It is however based on smartphone interfaces and does not have other modalities of interaction like gestures or vision-controlled controls. [13]. An example of reduced processing time was suggested by Md. Abdul Kaium Khan et al. and is a portable and wireless biometric attendance system. The system is portable and efficient, but limited only to tracking the attendance but not the use of smart methods of interaction or smart home automation. [14]. Towqir Ahmed Shaem et al. came up with a wireless fingerprint attendance system based on the use of NodeMCU in academic use. The system displays effective data transmission and biometrical authentication. The smart home is however not incorporated with smart perception and real time control systems which can be applied in smart home settings. [15].

### III. PROPOSED METHOD

The suggested approach uses a low-priced contactless appliance control application that is based on a framework of gesture recognition, run on TinyML, and combined with an ESP32-CAM microcontroller. This system is designed to work by activating the camera module, relay unit, wireless communication, and LCD display so as to create a stable working system. The ESP32-CAM is used to constantly take real-time hand pictures and send them to an edge-processing unit using Wi-Fi. The images obtained at the edge device are preprocessed, that is, by resizing and normalization, to be consistent to different lighting conditions. MediaPipe hand landmark detection model identifies important features like fingertip and joint positions and these features are then processed by a lightweight TinyML classifier to identify predefined hand gestures. To enhance reliability, a decision mechanism is used to eliminate invalid frames and ignore unknown gestures and thus reduces false activations. After a valid gesture can be detected, a control command is created and sent back to the ESP32-CAM which also triggers relay modules to switch on and off the household appliances, including lights and fans. At the same time, the 16x2 LCD shows the gesture and appliance state that have been identified, and the user can get real-time feedback. The cyclic operational mechanism allows controlling appliances in real-time in an energy efficient and reliable way using gestures on resource-limited hardware, which makes the suggested system applicable in the smart home, particularly in the case of the elderly and a disabled person.

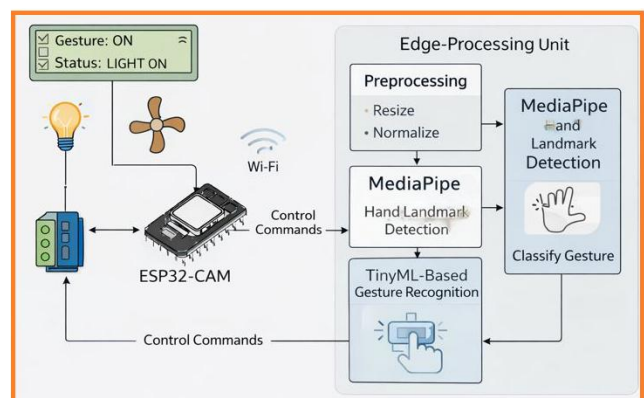


Fig. 1. Architecture of the proposed method

#### A. Hardware Setup

The ESP 32-CAM will serve as the main controller of the proposed system. It combines an ESP32 microcontroller with a camera module on board that

allows capturing images in real-time and communicating wirelessly. The ESP32-CAM will handle the role of taking pictures of hand gestures, sending them to the edge-processing unit using Wi-Fi, taking in control commands and operating relay modules to control appliances. The fact that it is low priced, small, and has built-in Wi-Fi makes it applicable to embedded vision applications.

#### 1) Camera Module (OV2640)

The OV2640 image sensor module attached to the ESP32-CAM provides images in real-time about hand gestures. It is capable of variable resolutions and offers good enough image quality to make gestures reliably and has minimal power requirements. The recognized images constitute the main input in the gesture recognition pipeline.

#### 2) Edge Processing Unit (Laptop)

The laptop serves as an edge processor in which processor intensive computations are carried out. It loads MediaPipe hand landmark detector model and performs image preprocessing, feature extracting and gesture classification using TinyML. Delegating these functions to the ESP32-CAM guarantees the low-latency, a high level of accuracy, and less computation workload on the microcontroller.

#### 3) Relay Module

The relay board will be an electrical interface between the ESP32-CAM and appliances used in the home. It enables the microcontroller to switch AC appliances like lights and fans that use high voltage to be safely controlled by low-voltage control signals. The relay module also provides electrical isolation and stability of the appliances.

#### 4) 16x2 LCD Display

This LCD of 16x2 is utilized to provide real-time information about the system (gestures identified and appliance state). It gives the user instant visual feedback, which assures him that he/she has successfully recognized gestures and controlled actions. LCD increases usability and transparency in the system.

#### 5) Power Supply Unit:

Controlled power supply gives the necessary operating voltage to ESP32-CAM, relay module and LCD display. Constant delivery of power can guarantee the steady work of the system and avoid the malfunction of the system caused by the changes in voltage.

#### 6) Household Appliances (Load)

The electrical appliances like lights and fans are also linked to the relay module and they are controlled loads in the system. These appliances are executed

according to the accepted hand gestures, which indicates the high level of usefulness of the suggested gesture-based system of controls.

### B. Algorithm

**Step 1:** Start the system by supplying power to the hardware setup.

**Step 2:** Initialize all hardware components, including the ESP32-CAM, camera module, relay unit, LCD display, and Wi-Fi communication.

**Step 3:** Load the MediaPipe hand landmark detection model on the edge-processing unit (laptop).

**Step 4:** Continuously capture real-time hand images using the ESP32-CAM.

**Step 5:** Transmit the captured images wirelessly to the edge-processing unit.

**Step 6:** Preprocess the received images by resizing and normalizing to match the model input requirements.

**Step 7:** Perform hand landmark detection to extract key features such as fingertip and joint positions.

**Step 8:** Check for the presence of a valid hand gesture based on extracted landmarks.

**Step 9:**

a) If a valid gesture is detected, classify the gesture using a TinyML-based classifier.

b) If no valid gesture is detected, discard the frame and return to Step 4.

**Step 10:** Generate a control command corresponding to the classified gesture.

**Step 11:** Transmit the control command to the ESP32-CAM via Wi-Fi.

**Step 12:** Activate the appropriate relay to control the corresponding appliance.

**Step 13:** Update the 16x2 LCD display with the recognized gesture and appliance status.

**Step 14:** Repeat Steps 4–13 continuously for real-time operation.

**Step 15:** Stop the system when power is turned off.

### C. Implementation

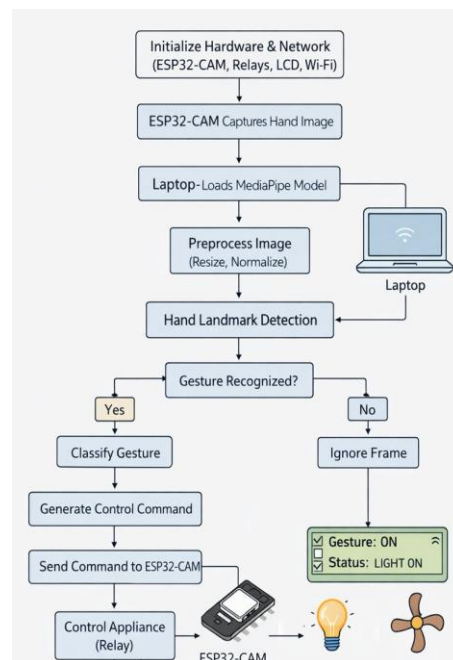


Fig. 2. Implementation of the flow chart

#### IV. EXPERIMENTAL RESULTS

The system of gesture recognition developed based on TinyML was successfully experimentally tested with the help of the designed hardware prototype with ESP32-CAM, relay module, 16x2 LCD, and household appliances (light and fan). The experiments were done inside a setting and in different lighting conditions to test the system performance, reliability and real time responsiveness. The gestures with both hands were done at varying distances and orientations before the camera to measure robustness. In the course of experimentation, the ESP32-CAM was able to capture live images of hands and wirelessly transfer them to the edge-processing unit without any apparent loss in packets. The hand landmark detection model using MediaPipe was able to detect key hand landmarks always and allowed good gesture recognition even in the presence of moderate background changes. The imageries that were used in preprocessing like normalization and resizing helped maintain consistency in performance under varying light conditions. The gesture classification model was able to identify predefined gestures and produce appropriate control commands. Incomplete gestures or invalid gestures were blocked successfully eliminating unintentional appliances activation. The relay module was fast in response to the commands received and the switching of the appliances was smooth with very little latency. The system proved to be good regarding real-time use, where movements of the hands and the reaction of the appliances took nearly no time. The LCD display showed the identified gesture and appliance status in real time and was an effective gesture feedback and control..

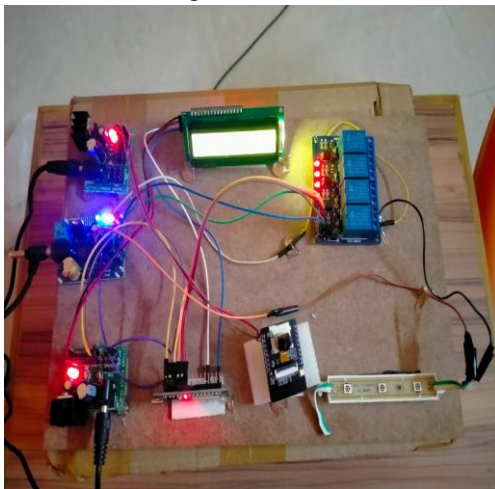


Fig. 3. Hardware setup for Receiver

To evaluate the accuracy of gesture recognition, the response time of the system, and the reliability of appliance control, experiments were carried out in an indoor setting with the usual amount of light..

##### A. Gesture Recognition Accuracy

The system was experimented using several set hand gestures that represented commands of controlling the appliances. Every gesture was repeated several times to determine the accuracy of classification..

TABLE I. GESTURE RECOGNITION ACCURACY

Gesture Type	Total Trials	Correctly Recognized	Accuracy (%)
Light ON	50	47	94.0
Light OFF	50	46	92.0
Fan ON	50	45	90.0
Fan OFF	50	46	92.0
<b>Overall</b>	<b>200</b>	<b>184</b>	<b>92.0</b>

The findings suggest that the system has good recognition rates in all the classes of gestures. Small misclassifications also took place because of the partial visibility of the hand and high speed of movement of the hand.

##### B. System Response Time Analysis

Response time was defined as the time taken by the system to react to the gesture by activating the appliance through the relay..

TABLE II. AVERAGE SYSTEM RESPONSE TIME

Operation Stage	Average Time (ms)
Image Capture (ESP32-CAM)	120
Wireless Transmission	180
Preprocessing & Landmark Detection	220
Gesture Classification	90
Command Transmission & Relay Actuation	110
<b>Total Response Time</b>	<b>720 ms</b>

Response time was defined as the time taken by the system to react to the gesture by activating the appliance through the relay.

##### C. Appliance Control Reliability

The reliability was tested by keeping the appliances active over long periods of time.

TABLE III. APPLIANCE CONTROL RELIABILITY

Appliance	Total Commands	Successful Operations	Success Rate (%)
Light	100	98	98.0
Fan	100	97	97.0
<b>Overall</b>	<b>200</b>	<b>195</b>	<b>97.5</b>

The fact that it was very successful proves the stability of operation of the relay, as well as stable communication between the edge-processing unit and ESP32-CAM.

#### D. Power and Cost Efficiency

The low power consumption of the ESP32-CAM-based system was because of edge-based processing and inference with a lightweight TinyML. The proposed design is much more affordable in terms of hardware costs and power consumption when compared to vision systems based on Raspberry Pi, yet offers credible performance.

#### E. Performance Comparison

The comparison of accuracy graph reveals that the proposed system based on gesture TinyML has better recognition accuracy ( $\approx 92\%$ ) as compared to the current systems ( $\approx 85\%$ ). This is largely enhanced by the powerful hand landmark detection and invalid frame filtering.

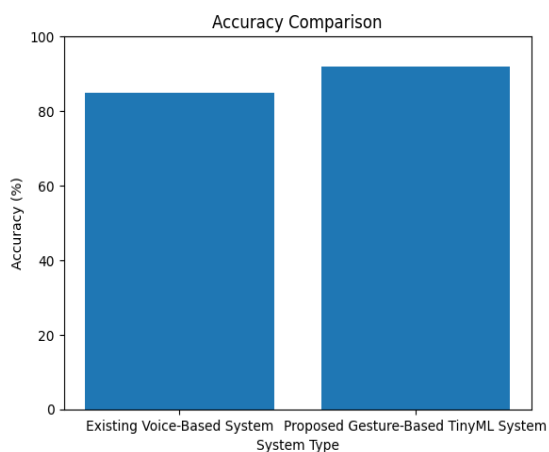


Fig. 4. Accuracy Comparison

Latency comparison graph shows that the proposed system will considerably decrease the response time. The current voice based systems have a higher latency (about 1200 ms) because of speech processing and dependence on the cloud whereas the proposed system has a lower latency (about 720 ms) since the system is based on edges..

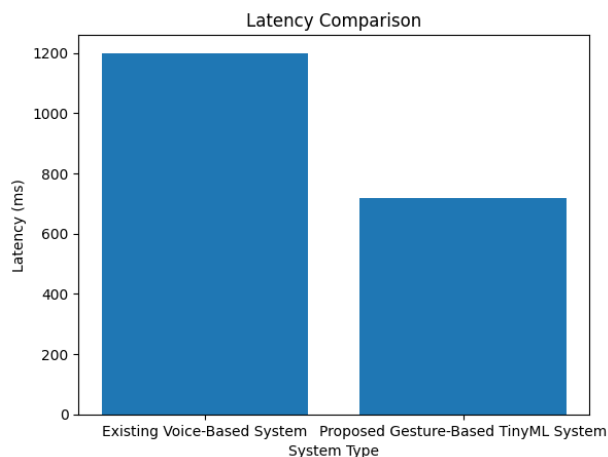


Fig. 5. Latency Comparison

## V. CONCLUSION AND FUTURE SCOPE

The architecture and software development of a gesture recognition-based appliance control system based on a TinyML on a low-cost ESP32-CAM microcontroller. The given system allows to intuitively and contactlessly control the appliances in the house after recognizing the hand gestures with embedded vision systems. With edge-based processing combined with an ESP32-CAM and a lightweight gesture classification model, the system manages to surmount the constraints of the traditional voice- and app-based home automation systems. The system is able to capture hand images in real-time, followed by pre-processing and hand landmarks detection with the help of the MediaPipe-based framework, and gesture classification with tinyML model. Known gestures are programmed to control commands and sent back to the ESP32-CAM to switch on relay modules to control appliances. The design experiment showed that there was a reliable gesture recognition, low response time, and consistent performance of appliance switching. An LCD display also made usability more convenient, as it was giving real-time feedback to the user. Subsequent applications can be directed towards the deployment of the complete gesture recognition pipeline directly on the ESP32-CAM with fully optimized TinyML models, and thus do away with the necessity to rely on an external edge-processing device. Remote monitoring, data logging, and intelligent decision-making based on advanced analytics can be performed with the help of integration with the cloud platforms. Also, the adaptive learning methods can be introduced so that the system could become increasingly recognizing as time went by.

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