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Embedded AI-Based Gesture Control System

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Abstract: This paper presents the design and implementation of an Embedded AI-Based Gesture Control System for Greenhouse Automation. The system provides a contactless and intelligent method to control greenhouse equipment using hand gestures. Conventional control methods, such as switches, remotes, or internet-based systems, may be inconvenient in humid agricultural environments and often require continuous connectivity. To address these issues, the proposed system uses a motion-based gesture recognition approach that operates completely offline. The system uses an MPU6050 accelerometer and gyroscope sensor to capture real-time hand motion data. This data is processed using a lightweight Artificial Intelligence (AI) model trained with sensor datasets and deployed on an ESP32 microcontroller using TensorFlow Lite. The trained model recognizes predefined gestures and converts them into control commands to operate greenhouse devices such as irrigation pumps, ventilation fans, lighting systems, and servo mechanisms through a relay interface. Additional environmental monitoring is carried out using sensors such as DHT11 for temperature and humidity, soil moisture sensors, and water level sensors, which help maintain suitable greenhouse conditions. The system works locally without requiring internet connectivity, ensuring reliability, low latency, and improved data privacy. Experimental implementation and testing show that the system can accurately recognize gestures and control greenhouse devices with fast response time and stable performance. The proposed system provides a low-cost, energy-efficient, and user-friendly solution for smart greenhouse automation and modern precision agriculture.
Keywords: Embedded AI, Gesture Recognition, Greenhouse Automation, ESP32 Microcontroller, MPU6050 Sensor, Smart Agriculture, Precision Farming, TensorFlow Lite.

I. INTRODUCTION

Automation has become an essential part of modern technology, improving efficiency and reducing manual effort in various fields, including agriculture. In greenhouse farming, maintaining proper environmental conditions such as irrigation, ventilation, and lighting is important for healthy plant growth. Traditional control methods usually rely on manual switches or remote controllers, which may be inconvenient and unsafe in humid greenhouse environments [8].

Gesture recognition offers a natural and contactless way for humans to interact with machines. Many existing gesture control systems use cameras, but these systems require high computational power, increased cost, and may raise privacy concerns. Therefore, sensor-based gesture recognition using motion sensors provides a more practical solution for embedded systems [3].

The proposed Embedded AI-Based Gesture Control System for Greenhouse Automation uses an MPU6050 accelerometer and gyroscope sensor to detect hand movements. The motion data is processed using a lightweight AI model deployed on an ESP32 microcontroller, which recognizes predefined gestures and controls greenhouse devices such as pumps, fans, and lights through relay modules. The system operates offline, making it reliable, energy-efficient, and suitable for smart greenhouse automation [3], [10].

A. Background

Traditional greenhouse systems mainly rely on manual control or simple automated timers to operate irrigation, ventilation, and lighting. These methods require frequent human involvement and may not always provide efficient control of environmental conditions [5].

With the advancement of smart agriculture, automation technologies are being introduced to improve greenhouse management. Sensor-based gesture recognition combined with embedded artificial intelligence provides a simple and efficient way to control greenhouse devices without physical contact, improving convenience, safety, and efficiency [1], [4].

B. Proposed Approach

The proposed system introduces an Embedded AI-Based Gesture Control System for Greenhouse Automation that allows users to control greenhouse equipment using simple hand gestures. The system provides a contactless and efficient way to operate devices such as irrigation pumps, fans, and lighting systems. It is designed to work offline and provide a reliable solution for greenhouse automation.

C. Key Points of the Proposed Approach

1) Gesture Detection using MPU6050: The system uses an MPU6050 accelerometer and gyroscope sensor to detect hand movements. The sensor captures motion data such as acceleration and orientation, which represent different gestures performed by the user [6].
2) AI-Based Gesture Recognition: The captured sensor data is processed using a lightweight Artificial Intelligence (AI) model. The model is trained to recognize predefined gestures and classify them into different control commands [2], [4].
3) Embedded Processing using ESP32: The trained AI model is deployed on the ESP32 microcontroller, which processes the gesture data and generates the appropriate control signals. The ESP32 acts as the main controller of the system [10].
4) Control of Greenhouse Devices: Based on the recognized gesture, the ESP32 sends signals to a relay module to operate greenhouse equipment such as irrigation pumps, ventilation fans, lighting systems, and servo motors [11].
5) Environmental Monitoring: Additional sensors such as DHT11, soil moisture sensors, and water level sensors are used to monitor environmental conditions inside the greenhouse and support efficient plant growth [8].
6) Offline and Energy Efficient Operation: The system works without internet connectivity, ensuring reliable operation in remote areas. It is designed to be low-cost, energy-efficient, and suitable for smart agriculture applications [4].

This approach demonstrates how gesture recognition and embedded AI can be used to develop a simple and effective greenhouse automation system [1].

II. LITERATURE SURVEY

Gesture recognition and automation technologies have gained significant attention in recent years due to their ability to improve human–machine interaction. Many researchers have explored different methods to control electronic devices using hand gestures.. These systems are widely used in applications such as smart homes, robotics, healthcare systems, and industrial automation. The main goal of gesture recognition systems is to provide a natural and contactless way for users to interact with machines [5].

Zhang et al. (2019) proposed a CNN-based hand gesture recognition system using depth sensors for human–computer interaction. Their research demonstrated that deep learning models can achieve high accuracy in gesture classification when large datasets are used for training. However, the system required high computational power and advanced hardware, which limits its use in low-cost embedded systems [4].

Patel and Thakkar (2019) developed a gesture-controlled smart home system that used an external camera and computer processing to detect hand gestures. The system was able to control household appliances through gesture commands. Although the system was effective, it depended on a computer for processing, which increased system complexity and reduced portability [5].

Kim et al. (2020) introduced lightweight convolutional neural network models designed specifically for embedded devices. Their work focused on reducing computational complexity while maintaining good gesture recognition accuracy. This research showed that optimized AI models can run efficiently on low-power embedded systems [2].

Singh and Sharma (2021) studied various IoT-based smart home automation systems and discussed challenges such as high implementation cost, system complexity, and dependence on internet connectivity. Their study highlighted the need for automation systems that are affordable, scalable, and capable of operating independently without cloud dependency.

Gupta and Mehta (2022) investigated hybrid sensor-based gesture recognition systems that combine data from cameras and motion sensors such as accelerometers and gyroscopes. Their results showed that motion sensors can provide reliable gesture detection with lower computational requirements, making them suitable for embedded applications [6].

From the literature survey, it is observed that many existing gesture recognition systems rely on camera-based technologies or high-performance computing platforms. These approaches often increase system cost, power consumption, and privacy concerns. Therefore, the proposed system focuses on sensor-based gesture recognition using the MPU6050 motion sensor combined with embedded AI on the ESP32 microcontroller. This approach provides a low-cost, energy-efficient, and offline solution suitable for greenhouse automation and smart agriculture applications [2], [11].

III. METHODOLOGY

The proposed system is developed by integrating motion sensing, embedded artificial intelligence, and greenhouse automation. First, the MPU6050 accelerometer and gyroscope sensor captures hand motion data when a user performs gestures. These sensor readings are used as input for gesture recognition [6], [7].

The collected data is processed using a lightweight AI model trained with motion sensor datasets and deployed on the ESP32 microcontroller using TensorFlow Lite. The AI model recognizes predefined gestures and converts them into control commands. Based on the detected gesture, the ESP32 activates greenhouse devices such as irrigation pumps, ventilation fans, lighting systems, and servo motors through a relay module [7].

Additional sensors like DHT11, soil moisture, and water level sensors monitor greenhouse conditions. The system operates offline, ensuring reliable and energy-efficient automation.

A. Hardware Architecture

1) Block Diagram

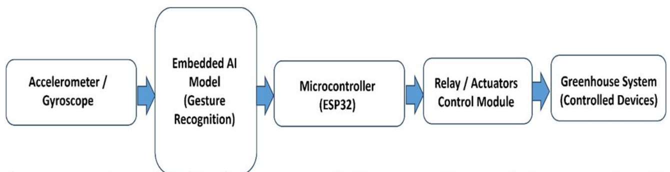

Fig 3.1 a): Block Diagram of Embedded AI-Based Gesture Control System for Greenhouse Automation

The hardware architecture of the proposed system consists of several components that work together to control greenhouse devices using hand gestures. First, the hand gesture performed by the user is detected by the MPU6050 accelerometer and gyroscope sensor, which captures motion data such as acceleration and orientation [11].

The captured sensor data is then sent to the ESP32 microcontroller, where the embedded AI model processes the data and identifies the performed gesture. After recognizing the gesture, the ESP32 sends control signals to the relay module, which acts as a switching interface [5], [11].

Finally, the relay module activates the required greenhouse devices such as irrigation pumps, ventilation fans, lighting systems, or servo motors based on the recognized gesture. This architecture enables efficient and contactless control of greenhouse systems [5], [8].

To improve system functionality, environmental monitoring sensors are integrated with the gesture control system. The DHT11 sensor measures temperature and humidity, while soil moisture and water level sensors monitor irrigation requirements. The ESP32 continuously collects data from these sensors and helps maintain suitable greenhouse conditions. This integration enhances automation efficiency, reduces manual intervention, and supports healthy plant growth in smart agriculture applications [8], [11].

2) Circuit Diagram

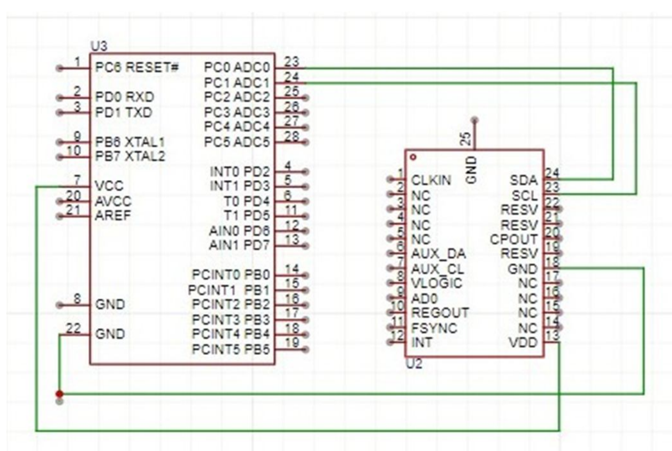

Fig 3.1 b): Circuit Diagram of MPU6050 Motion Sensor Interfaced with the Microcontroller

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The circuit diagram illustrates the interfacing of the MPU6050 motion sensor with the microcontroller used in the proposed gesture control system. The MPU6050 is an Inertial Measurement Unit (IMU) that combines a 3-axis accelerometer and a 3-axis gyroscope, which are used to measure motion, orientation, and angular velocity of the hand during gesture movements [3], [6].

In this circuit, the MPU6050 sensor communicates with the microcontroller using the I²C communication protocol. The SDA (Serial Data) pin of the sensor is connected to the SDA pin of the microcontroller, while the SCL (Serial Clock) pin is connected to the SCL pin. These two lines allow the microcontroller to receive motion data from the sensor. The VDD and VLOGIC pins of the MPU6050 are connected to the power supply, while the GND pin is connected to the system ground to complete the circuit [7], [11]. When a user performs a hand gesture, the MPU6050 detects changes in acceleration and angular rotation along the X, Y, and Z axes. These motion signals are transmitted to the microcontroller through the I²C interface. The microcontroller processes the received sensor data and extracts motion features that are used by the gesture recognition algorithm or trained AI model [3].

Based on the recognized gesture, the microcontroller generates the appropriate control signal to operate greenhouse devices such as irrigation pumps, ventilation fans, and lighting systems. Therefore, the MPU6050 sensor plays an important role in capturing accurate motion data required for reliable gesture recognition in the proposed system.

B. Software Architecture

The flowchart represents the software working process of the proposed gesture control system. First, the system starts and the ESP32 microcontroller initializes I²C communication with the MPU6050 sensor. This communication allows the microcontroller to receive motion data from the sensor [7], [11]. After initialization, the system reads accelerometer and gyroscope data from the MPU6050. These readings contain information about the hand's movement, orientation, and acceleration. The collected sensor data is then processed to extract important motion features, which help in identifying different hand gestures [6].

Next, the extracted data is passed to the trained Artificial Intelligence (AI) model, which analyzes the motion patterns and determines which gesture has been performed. The AI model compares the input data with previously trained gesture patterns to recognize the correct gesture [2]. Once the gesture is identified, the ESP32 executes the corresponding control action. The microcontroller sends signals to the control module or relay system to operate greenhouse devices such as pumps, fans, or lighting systems. After performing the action, the system continues monitoring new gestures, allowing continuous and real-time control of the greenhouse environment.

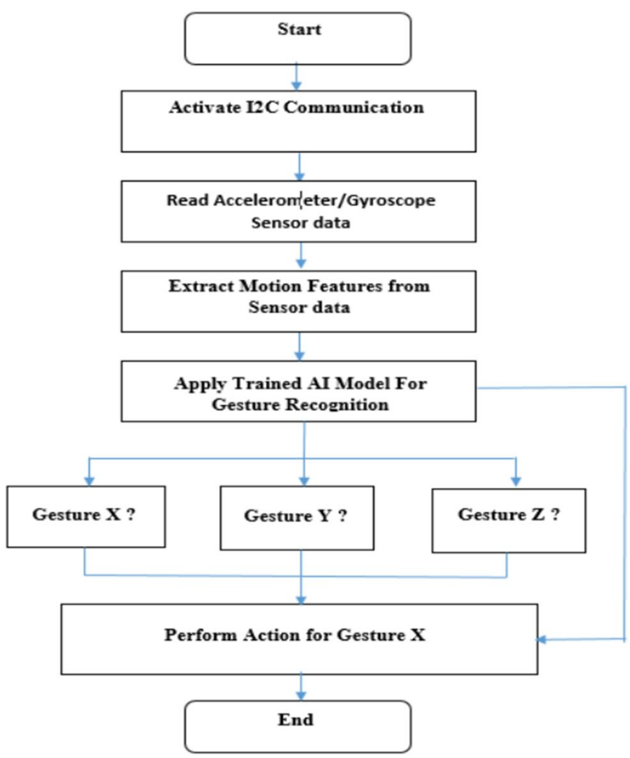

Fig 3.2: Flow Chart

IV. EXPERIMENTATION AND RESULTS

The proposed gesture control system was tested using the MPU6050 accelerometer and gyroscope sensor to collect motion data for different hand gestures. The sensor outputs six parameters representing motion in three axes: Ax, Ay, Az (accelerometer) and Gx, Gy, Gz (gyroscope). These values were visualized using the Arduino Serial Plotter, which displays real-time motion patterns generated by hand gestures.

During the training phase, multiple gestures such as UP, DOWN, LEFT, and RIGHT were performed repeatedly to collect motion data. Each gesture produced a unique waveform pattern in the serial plotter. These patterns were used to train the AI model for gesture recognition [11].

1) Gesture: UP

Fig 4.1: Sensor waveform for UP gesture

The UP gesture generates a distinct motion pattern in the MPU6050 accelerometer and gyroscope data. When the user moves their hand upward, noticeable changes occur in the acceleration and angular velocity values, especially along the vertical axis. These sensor readings form a unique sequence that is recognized by the AI model. By comparing the incoming data with previously trained patterns, the model accurately identifies the gesture as an UP movement and triggers the corresponding greenhouse control function.

2) Gesture: DOWN

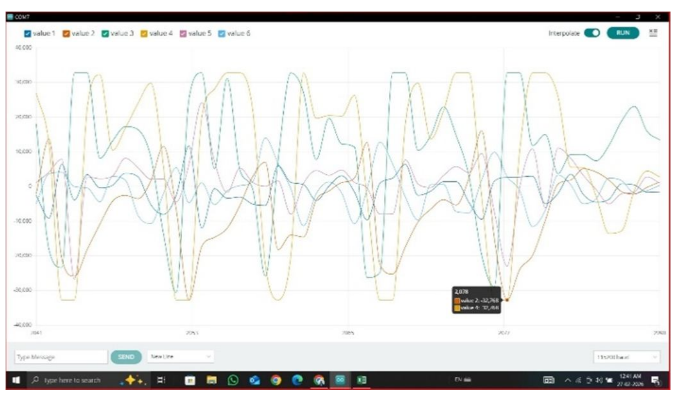

Fig 4.2: Sensor waveform for DOWN gesture

The DOWN gesture produces a distinct motion pattern in the MPU6050 sensor data. When the user moves their hand downward, the accelerometer detects changes in acceleration in the opposite direction of the UP gesture, while the gyroscope measures the corresponding angular movement. These unique sensor variations create a characteristic pattern that the AI model recognizes. By comparing the incoming data with trained gesture patterns, the model accurately identifies the gesture as a DOWN movement and triggers the assigned greenhouse control action.

3) Gesture: LEFT

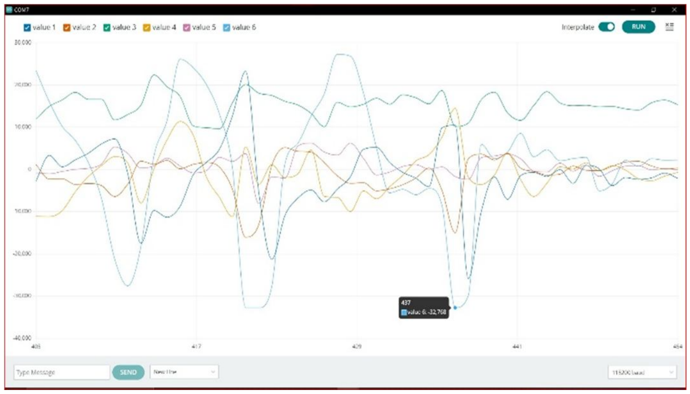

Fig 4.3: Sensor waveform for LEFT gesture

When the hand moves toward the left direction, the sensor readings show clear variations in the horizontal axis, allowing the system to distinguish the gesture. These characteristic changes in accelerometer and gyroscope data help the AI model accurately recognize left-hand movements and differentiate them from other gestures.

The LEFT gesture produces a unique motion pattern that helps the AI model accurately identify and classify left-hand movements.

4) Gesture: RIGHT

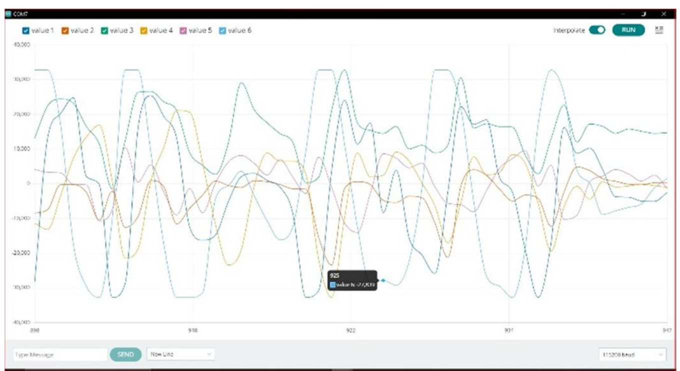

Fig 4.4: Sensor waveform for RIGHT gesture

The RIGHT gesture produces a waveform pattern opposite to the LEFT gesture, enabling the model to recognize rightward motion accurately. The experimental results show that each gesture generates a distinct sensor signal pattern, which allows the trained AI model to classify gestures with good accuracy. The system successfully interprets these gestures and triggers the corresponding control actions in the greenhouse automation system..

The results demonstrate the effectiveness of combining MPU6050-based motion sensing with embedded AI for reliable real-time gesture recognition.

V. CONTRIBUTION

This research presents the development of an Embedded AI-Based Gesture Control System for Greenhouse Automation, which provides a contactless and intelligent method for controlling greenhouse equipment. The system integrates motion sensing, embedded artificial intelligence, and automation technologies to improve greenhouse management [4].

One of the major contributions of this work is the use of an MPU6050 accelerometer and gyroscope sensor for gesture detection combined with an AI model deployed on the ESP32 microcontroller. This allows real-time gesture recognition and device control without the need for external computing systems [3], [4].

Another important contribution is the offline operation of the system, which eliminates dependency on internet connectivity or cloud-based processing. This improves system reliability, reduces latency, and makes the solution suitable for rural or remote agricultural environments [8].

The system also integrates multiple environmental sensors such as temperature, humidity, soil moisture, and water level sensors, enabling efficient monitoring and control of greenhouse conditions. This combination of gesture recognition and environmental monitoring provides a low-cost, energy-efficient, and user-friendly automation solution for smart agriculture.

Overall, this work demonstrates how embedded artificial intelligence and gesture recognition technology can be effectively used to develop practical and scalable solutions for modern greenhouse automation [1], [4].

VI. CONCLUSION

This paper presented the design and implementation of an Embedded AI-Based Gesture Control System for Greenhouse Automation. The proposed system uses an MPU6050 accelerometer and gyroscope sensor to capture hand motion data and recognize gestures using a lightweight AI model deployed on the ESP32 microcontroller [2]. Based on the recognized gesture, the system controls greenhouse devices such as irrigation pumps, ventilation fans, lighting systems, and servo mechanisms through a relay module [11].

The system operates offline without requiring internet connectivity, which improves reliability, reduces latency, and ensures data privacy. Experimental results obtained from sensor data visualization and gesture training demonstrate that different hand gestures produce distinct motion patterns, allowing the AI model to classify gestures effectively [2], [4], [6].

The proposed system provides a low-cost, energy-efficient, and user-friendly solution for smart greenhouse automation. By integrating gesture recognition with environmental monitoring sensors, the system improves convenience and efficiency in greenhouse management. This work highlights the potential of embedded artificial intelligence and gesture-based control systems in advancing modern agriculture and smart farming technologies [1], [4], [8].

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