

Smart Home Automation with Real-Time Energy Monitoring and Voice Control using ESP32

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ABSTRACT: With the rapid advancement of the Internet of Things (IoT), smart home automation systems have become increasingly popular for improving convenience, safety, and energy efficiency in modern homes. This research proposes an IoT-based smart home automation and energy monitoring system using the ESP32 microcontroller, integrated with Amazon Alexa, Google Assistant, and ESP RainMaker. The proposed system enables users to control household appliances remotely through voice commands and mobile applications via a cloud-based platform.

In addition to appliance control through relay modules, the system incorporates voltage and current sensors to monitor electrical parameters in real time. Using these measurements, the ESP32 calculates power consumption and total energy usage in kilowatt-hours (kWh). A 16×2 LCD display is used to show real-time information such as voltage, current, power consumption, energy usage, and device status. Furthermore, an overload protection mechanism is implemented to automatically disconnect appliances if power consumption exceeds a predefined limit, ensuring electrical safety.

The proposed system provides an efficient, cost-effective, and scalable solution for smart home automation while also enabling users to monitor and manage their energy consumption effectively. This system can be further expanded to support additional sensors and advanced smart home applications in the future.

Keywords: IoT, Smart Home Automation, ESP32, Energy Monitoring, Alexa Integration, Google Assistant, ESP RainMaker, Relay Control.

1. INTRODUCTION

The rapid evolution of the Internet of Things (IoT) has significantly transformed modern living by enabling the development of smart home automation systems. These systems allow users to remotely control and monitor household appliances through internet-connected devices, improving convenience, safety, and energy efficiency in residential environments.

The availability of low-cost and high-performance microcontrollers such as the ESP32 has made it easier to design efficient IoT-based automation systems. The ESP32 integrates built-in Wi-Fi connectivity, allowing seamless communication between hardware devices, cloud platforms, and user interfaces such as mobile applications and voice assistants.

In this paper, we propose a smart home automation and

energy monitoring system based on the ESP32 microcontroller, integrated with Amazon Alexa, Google Assistant, and ESP RainMaker cloud platform. The system enables users to control appliances such as lights and fans using voice commands, mobile applications, or manual switches.

In addition to automation features, the system incorporates voltage and current sensors to monitor electrical parameters of connected appliances. The collected data are used to calculate real-time power consumption and total energy usage, allowing users to track electricity consumption and improve energy management. A 16×2 LCD display provides real-time system status and electrical data locally.

Furthermore, an overload protection mechanism is included in the system to automatically disconnect appliances if excessive power consumption is detected. This feature improves electrical safety and prevents potential damage to connected devices.

The proposed system provides a cost-effective, scalable, and intelligent solution for modern smart home environments, combining appliance automation with energy monitoring and safety features.

2. LITERATURE SURVEY

The rapid advancement of the Internet of Things (IoT) has significantly contributed to the development of smart home automation and energy monitoring systems. Several researchers have explored different approaches combining automation, energy efficiency, and remote-control technologies.

Early work in smart home automation focused primarily on remote appliance control using wireless communication technologies. For instance, Stolojescu-Crişan et al. (2021) proposed an IoT-based smart home system integrating sensors and actuators to automate household operations and improve user convenience. However, their work mainly emphasized automation without detailed energy monitoring capabilities.

Recent studies have shifted towards integrating energy monitoring with automation. Muhammed et al. (2022) developed an IoT-based home energy monitoring system capable of measuring real-time energy consumption and remotely controlling loads. Their system provided accurate monitoring but lacked advanced user interaction features such as voice control.

With the emergence of low-cost microcontrollers, the ESP32 has become widely used in smart home applications due to its built-in Wi-Fi and processing capabilities. Several researchers have utilized ESP32 for automation systems. Kakani et al. (2024) designed a smart home automation system using ESP32 and Blynk, enabling appliance control through mobile applications and manual switches. However, their system did not incorporate detailed energy monitoring or analysis features.

Similarly, other studies have focused on energy monitoring using IoT technologies. El-Khozondar et al. (2024) proposed a smart energy monitoring system using ESP32 that provides real-time data visualization and consumption analysis. Their system demonstrated the importance of real-time monitoring in optimizing energy usage and reducing costs.

Further research has explored integrated systems combining automation and energy management. Sureshkumar et al. (2024) presented an IoT-based smart home energy management system that uses multiple sensors to monitor and control household energy usage. While effective, the system complexity and cost remain significant challenges.

In addition, voice-controlled smart home systems have gained popularity with the rise of virtual assistants such as Amazon Alexa and Google Assistant. Studies have shown that integrating voice control enhances user convenience and accessibility, particularly for elderly and disabled users. However, many of these systems focus primarily on automation and lack real-time energy monitoring features.

Despite these advancements, several challenges remain in existing systems. Many solutions either focus on automation or energy monitoring but fail to effectively integrate both functionalities into a single system. Additionally, issues such as system cost, complexity, real-time responsiveness, and lack of safety mechanisms like overload protection are still areas of concern.

3. METHODOLOGY

The proposed smart home automation and energy monitoring system is designed using the ESP32 microcontroller as the central processing unit. The system follows a layered architecture consisting of the user layer, cloud layer, and device layer, enabling seamless communication between users and hardware components.

At the user layer, the system accepts input through voice assistants such as Amazon Alexa and Google Assistant, as well as through a mobile application integrated with the ESP RainMaker cloud platform. These inputs are transmitted to the cloud layer, where the commands are processed and routed to the ESP32 via a Wi-Fi network.

The ESP32 microcontroller acts as the core controller in the device layer. It receives control signals from the cloud platform and processes them to operate connected appliances. The ESP32 is interfaced with a relay module, which is responsible for switching electrical loads such as lights and fans ON or OFF based on user commands.

For energy monitoring, the system incorporates voltage and current sensors connected to the load. The voltage sensor measures the supply voltage, while the current sensor measures the current drawn by the appliance. These sensor readings are continuously fed into the ESP32 for processing.

The power consumption is calculated using the relation:

$$P = V \times I$$

The energy consumption is further computed over time in kilowatt-hours (kWh), allowing users to monitor their electricity usage effectively.

A 16×2 LCD display is integrated into the system to provide real-time feedback. The display shows parameters such as voltage, current, power consumption, total energy usage, and appliance status, enabling local monitoring without the need for a mobile interface.

To enhance system safety, an overload protection mechanism is implemented. If the calculated power exceeds a predefined threshold, the ESP32 automatically deactivates the corresponding relay, thereby disconnecting the load and preventing electrical damage.

The entire system is developed using the Arduino IDE, ensuring ease of programming, scalability, and cost-effectiveness. The proposed methodology ensures efficient integration of automation, real-time monitoring, and safety features within a single IoT-based platform.

the system ensures real-time synchronization between the cloud platform and hardware, enabling immediate response to user commands. The use of Wi-Fi connectivity in ESP32 allows continuous data transmission and remote monitoring without additional hardware modules. The modular design of the system makes it easy to expand by adding more sensors or appliances in the future.

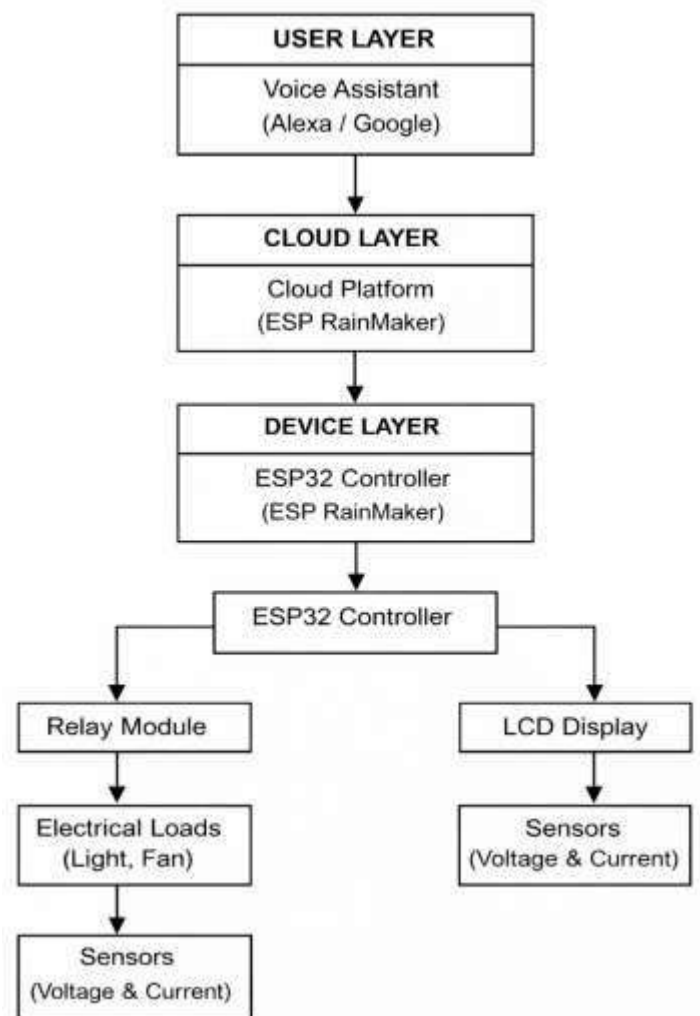


Fig. 1: Block Diagram

4. Hardware Implementation

1. ESP32 Microcontroller

The ESP32 microcontroller acts as the central control unit of the system. It provides built-in Wi-Fi connectivity, enabling communication with the cloud platform and voice assistants such as Amazon Alexa and Google Assistant. The ESP32 processes user commands and controls connected devices accordingly.



Fig 2. ESP32

2. Relay Module

A 4-channel relay module is used to control electrical appliances. It acts as an interface between low-voltage control signals from the ESP32 and high-voltage household devices such as lights and fans.



Fig 3. 4-Channel Relay Module

3. Power Supply Unit

A regulated power supply is used to provide stable voltage to the ESP32 and relay module. Proper power regulation ensures reliable system operation.



Fig 4. Power Supply

4. Electrical Loads

The system controls household appliances such as lights and fans through the relay module. These loads represent real-world devices used in residential environments.



Fig 5. Load

5. Voltage Sensor Module

The voltage sensor measures the supply voltage and converts it into a low-level analog signal suitable for the ESP32. This helps monitor voltage variations and ensures safe operation.



Fig 6. Voltage Sensor

6. Current Sensor Module

The current sensor (ACS712) measures the current flowing through the load. It converts the magnetic field generated by current into an electrical signal that can be read by the ESP32.



Fig 7. Current Sensor

7. Energy Monitoring Circuit

The combination of voltage and current sensors forms the energy monitoring system. The ESP32 calculates real-time power consumption using:

$$P = V \times I$$

This enables continuous tracking of energy usage.

8. Overload Protection System

An overload protection mechanism is implemented to enhance system safety. If power consumption exceeds a predefined threshold, the ESP32 automatically turns OFF the relay, preventing damage to appliances.

9. 16×2 LCD Display

A 16×2 LCD display is used to show real-time data such as voltage, current, power, energy consumption, and device status. This provides immediate local feedback to the user.

5. Software Implementation

The proposed smart home automation and energy monitoring system is developed using the Arduino IDE and implemented on the ESP32 microcontroller. The ESP32 serves as the central processing unit and connects to a Wi-Fi network to enable communication with cloud platforms such as ESP RainMaker and Sinric Pro.

The system supports both mobile-based and voice-based control. The ESP RainMaker application provides a user-friendly interface through which users can monitor and control connected appliances in real time. Users can switch devices ON/OFF, view device status, and monitor energy consumption remotely using the mobile application.

In addition to mobile control, the system integrates voice assistants such as Amazon Alexa and Google Assistant. These voice assistants use Natural Language Processing (NLP) to interpret user voice commands and convert them into machine-readable instructions. The processed commands are transmitted via the Sinric Pro cloud platform to the ESP32 over the internet.

The ESP32 continuously maintains communication with the cloud server and listens for incoming commands. Upon receiving a command, the microcontroller processes it and controls the relay modules to switch electrical appliances such as lights and fans ON or OFF. This enables seamless real-time control of devices from anywhere.

To implement system functionality, several software libraries are utilized. These include Wi-Fi libraries for network connectivity, Sinric Pro and ESP RainMaker libraries for cloud communication, sensor libraries for voltage and current measurement, and LiquidCrystal_I2C libraries for LCD interfacing.

The system also performs continuous monitoring of electrical parameters using voltage and current sensors. The ESP32 reads analog values from these sensors and calculates real-time power consumption using the formula: $P = V \times I$

The energy consumption is calculated over time in kilowatt-hours (kWh) by integrating power usage, allowing users to analyze electricity consumption patterns.

To ensure safety, an overload protection algorithm is implemented in the software. A predefined threshold value (e.g., 1000 W) is set, and if the measured power exceeds this limit, the ESP32 automatically turns OFF the corresponding relay module, disconnecting the load and preventing damage.

A 16×2 LCD display is integrated into the system to provide real-time local feedback. The display shows important parameters such as voltage, current, power consumption, total energy usage, and appliance status, enabling users to monitor the system without relying solely on the mobile application.

Additionally, the system can be extended to include environmental monitoring using DHT11 or DHT22 sensors for measuring temperature and humidity. These values can also be transmitted to the cloud platform for

remote monitoring.

The software architecture ensures reliable communication, real-time responsiveness, and efficient control of smart home devices. The integration of ESP RainMaker, Sinric Pro, and NLP-based voice processing enhances user convenience, system flexibility, and scalability, making the solution suitable for modern IoT-based smart home applications.

6. Results and Discussion (Final Improved Version)

The proposed smart home automation and energy monitoring system was successfully implemented and tested under real-time conditions. The experimental setup included an ESP32 microcontroller, relay module, voltage and current sensors, LCD display, and multiple electrical loads such as LED bulbs, as shown in the circuit implementation.

During testing, the system demonstrated reliable connectivity with cloud platforms and maintained stable communication over Wi-Fi. Commands given through Amazon Alexa, Google Assistant, and the ESP RainMaker mobile application were successfully transmitted via the cloud and executed by the ESP32 with minimal delay. The response time of the system was observed to be within acceptable limits, ensuring smooth and real-time control of connected appliances.

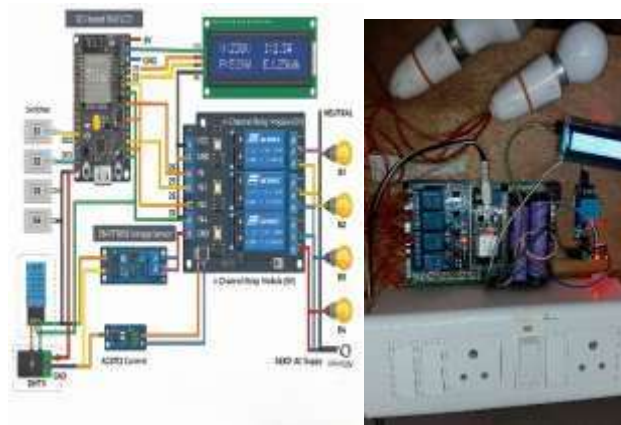


Fig. 8: Circuit implementation of the proposed system showing ESP32 interfaced with relay module, voltage sensor (ZMPT101B), current sensor (ACS712), and connected electrical loads.

Fig. 9: Complete hardware setup of the smart home automation system with ESP32, relay module, sensors, power supply, and 16×2 LCD display for real-time monitoring.

The relay module successfully controlled the switching of electrical loads such as bulbs, demonstrating accurate ON/OFF operation based on user commands. The system responded promptly to inputs received through the cloud platform, confirming proper integration between hardware and software components. The experimental setup, as illustrated in Fig. 8 and Fig. 9, verifies the effective implementation of the proposed smart home automation system.

The voltage and current sensors continuously monitored electrical parameters of the connected loads. These readings were processed by the ESP32 to compute real-time power consumption, and the results were displayed on the LCD. During experimentation, voltage values in the range of 220–240 V were observed, while current values varied depending on the load, resulting in realistic and consistent power measurements. The system calculated cumulative energy consumption in kilowatt-hours (kWh), enabling users to track electricity usage over time. The observed values were found to be consistent with the expected consumption of common household appliances such as LED bulbs and fans.



Fig. 10 shows the real-time output displayed on the LCD, including voltage, current, power, and energy values. This confirms that the system is capable of continuous monitoring and accurate visualization of electrical parameters.

Load	Voltage (V)	Current (A)	Power (W)	Energy (KWh)
No Load	230	0.00	0	0.00
Single Led Bulb	230	0.05	11.5	0.01
Two Led Bulb	230	0.10	23.0	0.02
Bulb + Fan	230	0.30	69.0	0.05
Multiple Loads	230	0.47	107.7	0.10

Table 1: Experimental readings of voltage, current, power, and energy consumption for different load conditions.

The overload protection feature was evaluated by setting a predefined threshold value. When the measured power exceeded this limit, the ESP32 automatically deactivated the relay module, thereby disconnecting the load. This demonstrates the system's capability to enhance electrical safety by preventing overload conditions.

Overall, the results demonstrate that the proposed system is reliable, cost-effective, and suitable for smart home applications. The integration of IoT technologies, cloud platforms, and voice assistants provides enhanced user convenience through remote and hands-free control of appliances.

7. Applications

The proposed smart home automation and energy monitoring system can be applied in several real-time scenarios where continuous monitoring and control of electrical devices are required.

The system can be effectively used in residential smart homes, where users can control appliances such as lights, fans, and other devices in real time using mobile applications or voice commands. This enhances convenience and improves energy efficiency in daily household operations.

In energy management systems, the solution enables real-time monitoring of power consumption and energy usage. Users can track electricity consumption patterns and take necessary actions to reduce energy wastage, making it suitable for energy-efficient homes.

The system is also applicable in elderly and assisted living environments, where voice-controlled operation allows users to control appliances without physical effort. This improves accessibility and safety for elderly and physically challenged individuals.

In smart offices and commercial buildings, the system can be used to monitor and control multiple electrical loads remotely. Real-time monitoring helps in reducing unnecessary energy consumption and optimizing operational efficiency.

The proposed system can also be implemented in industrial monitoring systems for controlling low-power equipment and monitoring energy usage. The overload protection feature ensures safety by preventing equipment damage due to excessive power consumption.

Additionally, the system is suitable for IoT-based remote monitoring applications, where devices can be controlled and monitored from any location through cloud platforms. This makes it useful for applications such as smart hostels, rental properties, and remote infrastructure management.

8. Conclusion

The proposed smart home automation and energy monitoring system based on the ESP32 microcontroller has been successfully designed and implemented. The system integrates real-time appliance control with energy monitoring, enabling users to operate electrical devices through mobile applications and voice assistants such as Amazon Alexa and Google Assistant.

The experimental results demonstrate that the system provides reliable performance in terms of device control, real-time monitoring, and communication through cloud platforms such as ESP RainMaker and Sinric Pro. The voltage and current sensors effectively measured electrical parameters, and the ESP32 accurately calculated power and energy consumption, which were displayed on the LCD in real time.

The inclusion of an overload protection mechanism enhances system safety by automatically disconnecting loads when the power exceeds a predefined threshold. Additionally, the integration of Natural Language Processing (NLP) through voice assistants improves user convenience by enabling hands-free control.

Overall, the system is cost-effective, scalable, and suitable for modern smart home applications. It can be further extended by incorporating additional sensors, data analytics, and machine learning techniques for advanced energy optimization and predictive control.

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