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Design and Performance Evaluation of an IoT-Based Voice-Controlled Home Automation System

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***Abstract*— The Internet of Things (IoT) has transformed home automation by enabling intelligent monitoring and remote control of household appliances. This paper presents the design and performance evaluation of a low-cost voice-controlled home automation system using the ESP8266 NodeMCU development board and Amazon Alexa. The developed system enables users to control household appliances through voice commands and manual push-button operation, providing improved accessibility and operational flexibility. System firmware was developed using the Arduino Integrated Development Environment (IDE), while Amazon Alexa served as the user interface for voice-based control. Functional testing demonstrated reliable and consistent operation of all connected loads under both voice and manual control. The proposed system provides a cost-effective, reliable, and user-friendly solution for residential automation, demonstrating the potential of open-source IoT technologies for improving convenience and accessibility, particularly for elderly and physically challenged users.**

Keywords—Internet of Things, Home Automation, ESP8266, Amazon Alexa, Voice Control, Smart Home.

I INTRODUCTION

The Internet of Things (IoT) has become one of the of the most transformative technologies of the twenty-first century, enabling physical devices to communicate, exchange data, and perform intelligent tasks through the Internet with minimal human intervention (Khan et al., 2023; Alshahrani & Ahmed, 2024). By integrating embedded systems, wireless communication, cloud computing, and sensor technologies, IoT has significantly improved automation across various sectors, including healthcare, agriculture, transportation, industrial automation, environmental monitoring, and residential applications. Among these areas, smart home automation has gained considerable attention due to its ability to enhance convenience, security, energy efficiency, and the overall quality of life (Winarno & Affandi, 2022; Rahman et al., 2023).

Smart home automation enables users to monitor and control household appliances remotely using Internet-connected devices such as smartphones, tablets, and computers. Recent developments in cloud computing and artificial intelligence have further enhanced these systems through the introduction of voice-enabled virtual assistants, including Amazon Alexa, Google Assistant, and Apple Siri (Amazon, 2023; Shakaramiro et al., 2024). These platforms allow users to operate household appliances using simple voice commands, eliminating the need for physical interaction with switches. Such functionality is particularly beneficial to elderly individuals and people with physical disabilities, providing greater independence and ease of operation in everyday activities (Patel & Singh, 2025). Despite these advancements, several challenges continue to hinder the widespread adoption of smart home technologies. Many commercially available systems are expensive because they rely on proprietary hardware and software platforms. Others require complex installation procedures, making deployment difficult for average users.

In addition, several IoT-based home automation systems reported in the literature depend on short-range communication technologies such as Bluetooth, limiting operational distance and restricting remote accessibility. These limitations highlight the need for affordable, reliable, and user-friendly home automation systems developed using open-source technologies that support efficient voice-based and remote control. The ESP8266 NodeMCU development board has emerged as a suitable platform for IoT applications (Espressif Systems, 2022; Rizky et al., 2023). This is because of its integrated Wi-Fi capability, compact design, low power consumption, and low implementation cost. Its compatibility with the Arduino Integrated Development Environment (IDE) simplifies software development while reducing hardware complexity by eliminating the need for external Wi-Fi modules. When integrated with Amazon Alexa, the ESP8266 Node MCU provides an effective and scalable solution for developing intelligent voice-controlled home automation systems. This paper presents the design, implementation, and performance evaluation of a low-cost IoT-based voice-controlled home automation system using the ESP8266 NodeMCU development board and the Amazon Alexa application. The developed system integrates wireless communication, voice recognition, and relay-based switching to provide reliable control of multiple household appliances through voice commands, while incorporating manual push-button switches to

ensure uninterrupted operation during temporary network interruptions. Functional testing demonstrated reliable and consistent performance under both voice-controlled and manual operating conditions. The proposed system provides a practical, cost-effective, and user-friendly smart home solution that demonstrates the potential of open-source IoT technologies for intelligent residential automation, particularly in resource-constrained environments.

II. LITERATURE REVIEW

The increasing adoption of the Internet of Things (IoT) has stimulated extensive research into smart home automation systems that improve convenience, accessibility, and energy management through intelligent control of household appliances. Recent developments have focused on integrating wireless communication technologies with embedded controllers and voice recognition platforms to provide users with seamless remote access to home devices.

Several studies have explored Bluetooth-based home automation because of its simplicity and low implementation cost (Rahman et al., 2023; Patel & Singh, 2025). Shehu (2023) developed a voice-controlled home automation system using an Arduino Uno and a Bluetooth communication module, allowing users to operate household appliances through an Android application. Similarly, Desai and Khanna implemented an Arduino-based automation system in which Bluetooth served as the communication interface between an Android device and the control unit. Although these systems demonstrated reliable appliance control, their operation was limited by the short communication range of Bluetooth technology, restricting users to local control (Khan et al., 2022).

Other researchers have adopted GSM communication to overcome the distance limitations associated with Bluetooth. (Singh et al. 2015) proposed a GSM-based home automation system in which Short Message Service (SMS) commands were used to switch household appliances remotely. (Smith et al. 2019) further enhanced GSM-based automation by integrating environmental sensors for monitoring temperature, humidity, lighting, and motion. While GSM technology extends communication beyond local networks, the dependence on cellular services introduces additional communication costs, message delays, and reduced responsiveness when compared with Internet-based control.

Voice-enabled home automation has also attracted considerable research interest. (Celebre et al. 2015) developed a Siri-based home automation system that enabled appliance control through voice commands on Apple iOS devices. The system achieved high recognition accuracy but was limited to Apple's ecosystem, thereby reducing accessibility for users of other mobile platforms. More recent smart home solutions increasingly integrate cloud-based voice assistants to provide more natural and convenient interaction between users and household devices. The ESP8266 NodeMCU has become a preferred

platform for IoT applications because of its integrated Wi-Fi capability, low cost, compact architecture, and compatibility with open-source development tools (Winarno & Affandi, 2022; Rizky et al., 2023). Combined with cloud-based voice assistants such as Amazon Alexa, the platform provides a practical approach for implementing affordable smart home automation without requiring additional communication modules.

Although significant progress has been reported in the literature, many existing systems remain constrained by limited communication range, dependence on proprietary hardware, platform restrictions, or high implementation costs. These limitations highlight the need for a flexible, low-cost, and user-friendly home automation system capable of supporting reliable voice-controlled operation using open-source technologies. Accordingly, this study presents the design and performance evaluation of an IoT-based voice-controlled home automation system using the ESP8266 NodeMCU development board and Amazon Alexa to provide an affordable and practical solution for intelligent residential automation (Arzaq et al., 2024).

III. Materials and Methods

3.1 System Architecture

The proposed home automation system was designed to provide intelligent control of household electrical appliances using voice commands and manual switching. The system consists of four major functional units: the power supply unit, the ESP8266 NodeMCU development board, a four-channel relay module, and the Amazon Alexa mobile application. Figure 1 illustrates the overall architecture of the developed system.

The ESP8266 NodeMCU serves as the central controller responsible for processing user commands and coordinating communication between the connected appliances and the cloud-based Alexa platform through a Wi-Fi network. Voice commands issued by the user are transmitted via Amazon Alexa to the ESP8266, which activates the appropriate relay channel to switch the corresponding electrical load. Manual push-button switches are incorporated to provide local control whenever Internet connectivity is unavailable, thereby improving the reliability and flexibility of the system.

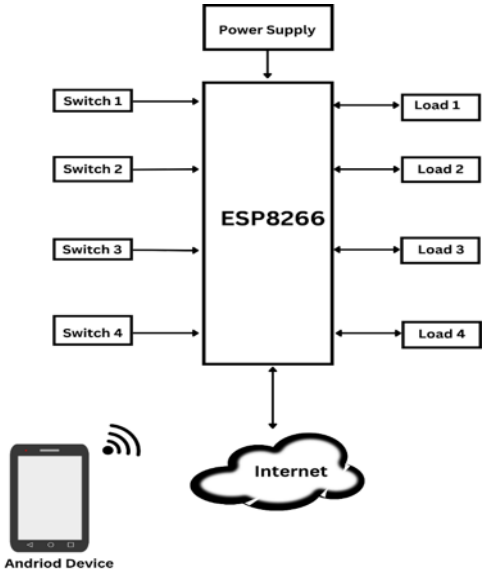

Figure 1: Block diagram of the System Architecture

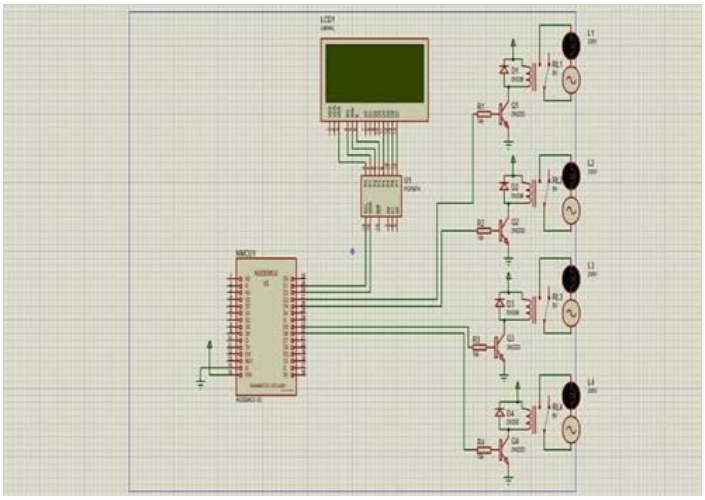

Figure 2: Circuit diagram of the home automation system

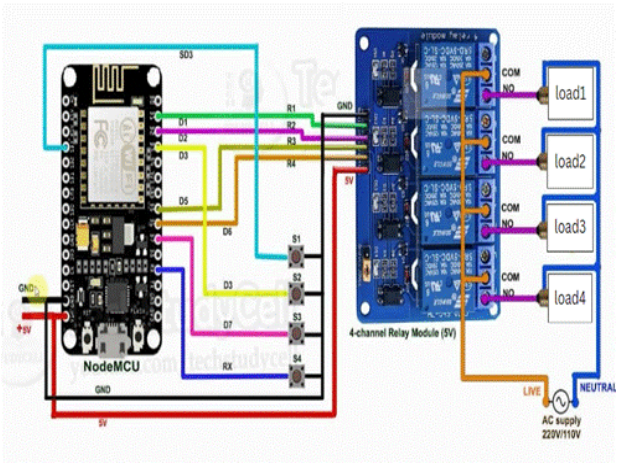

Figure 3: Schematic diagram of the home automation system

3.2 Hardware Components

The hardware implementation comprises a 5 V switched-mode power supply (SMPS), an ESP8266 NodeMCU development board, a four-channel relay module, LED lamps, a DC fan, and an electrical outlet representing typical household loads.

The ESP8266 NodeMCU functions as both the processing and communication unit because of its integrated Wi-Fi capability, low power consumption, compact architecture, and compatibility with the Arduino IDE. The four-channel relay module provides electrical isolation between the low-voltage control circuit and the high-voltage household appliances, allowing independent switching of each connected load. The switched-mode power supply provides a stable regulated DC voltage required for reliable operation of the control circuit.

3.3 Software Development

The system firmware was developed using the Arduino Integrated Development Environment (IDE) in C/C++. The control algorithm initializes the ESP8266 NodeMCU, establishes communication with the local Wi-Fi network, and continuously monitors incoming commands from the Amazon Alexa platform. Upon receiving a valid command, the controller energizes the corresponding relay channel to switch the selected appliance as contained in Figure 2 and 3 respectively.

The Amazon Alexa mobile application serves as the user interface through which connected devices are discovered, configured, and controlled using voice commands. The application communicates with the ESP8266 through the wireless network, enabling convenient real-time control of household appliances.

3.4 System Operation

The operational sequence begins when the ESP8266 NodeMCU connects to the available Wi-Fi network after power-up. Once communication with the Alexa platform is established, the connected appliances become available for voice control through the registered mobile device. User commands are interpreted by Amazon Alexa and transmitted to the microcontroller, which processes each command and activates the corresponding relay channel. The switching status is immediately reflected in the connected appliance.

To improve operational reliability, manual push-button switches are integrated into the system, allowing users to control appliances directly without relying on Internet connectivity. This dual-mode operation enhances system flexibility while ensuring uninterrupted appliance control under different operating conditions as shown in Table 1.

Table 1 summarizes the functional performance of the developed home automation system during experimental evaluation.

Load	Result (Voice Control)	Result (Manual Control)
Load 1	ON/OFF	ON/OFF
Load 2	ON/OFF	ON/OFF
Load 3	ON/OFF	ON/OFF
Load 4	ON/OFF	ON/OFF

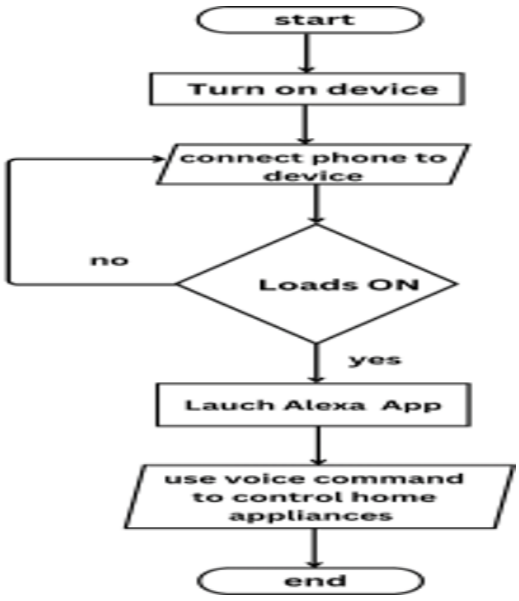

Figure 4: Flowchart of the Alexa-based home automation process

Figure 5: Final prototype of the home automation system

IV. Results and Discussion

The developed IoT-based voice-controlled home automation system was implemented and evaluated to determine its operational performance under practical conditions. Performance evaluation focused on the responsiveness and reliability of the system when appliances were controlled using both Amazon Alexa voice commands and manual push-button switches as indicated in the Alexa - based automation process of Figure 4.

Following successful hardware integration and software configuration, the ESP8266 NodeMCU established a stable connection with the wireless network and synchronized with the Amazon Alexa application as shown in Figure 5. The connected appliances were automatically detected by the application and assigned unique identifiers, enabling users to control each appliance independently through voice commands. Functional testing showed that the developed system responded correctly to all valid voice commands issued through Amazon Alexa (Shakaramiro et al., 2024). Corresponding relay channels were activated without observable communication failure, resulting in successful switching of the connected electrical appliances. Similarly, manual push-button operation provided immediate local control, demonstrating that the system remained operational even when voice control was unavailable. This dual-mode functionality significantly improves operational reliability and enhances user flexibility.

The performance of the developed prototype confirms the effectiveness of integrating the ESP8266 NodeMCU with Amazon Alexa for residential automation applications. The embedded Wi-Fi capability (Espressif Systems, 2022) of the ESP8266 ensured reliable communication without requiring additional networking hardware, thereby reducing implementation cost and system complexity. Furthermore, the relay interface provided effective electrical isolation between the low-voltage control circuit and the connected household appliances, contributing to safe and dependable operation.

The developed system offers several practical advantages over many conventional home automation solutions. First, it utilizes readily available open-source hardware and software, making implementation economical and accessible. Second, the incorporation of voice control improves user convenience and accessibility (Patel & Singh, 2025), particularly for elderly individuals and persons with physical disabilities. Third, the inclusion of manual push-button switches provides operational redundancy, ensuring uninterrupted appliance control during temporary network interruptions.

Overall, the experimental results demonstrate that the proposed system satisfies the primary design objectives by providing reliable, responsive, and cost-effective control of household appliances.

The study further confirms the suitability of open-source IoT technologies for developing intelligent residential automation systems capable of supporting future enhancements such as energy management, smart security, and predictive automation.

V. Conclusion

This paper presented the design and performance evaluation of an IoT-based voice-controlled home automation system using the ESP8266 NodeMCU development board and Amazon Alexa.

The developed system successfully integrated wireless communication, voice recognition, and relay-based switching to enable reliable control of household electrical appliances through both voice commands and manual push-button operation. Functional evaluation confirmed that all connected appliances responded accurately and consistently under the two operating modes, demonstrating the reliability and practicality of the proposed design.

The use of open-source hardware and software significantly reduced the implementation cost while maintaining satisfactory performance, making the system suitable for residential applications, particularly in resource-constrained environments. In addition, the incorporation of manual control enhanced operational flexibility by ensuring uninterrupted appliance control during temporary network interruptions.

The developed prototype demonstrates the potential of IoT and voice-assisted technologies in improving convenience, accessibility, and user comfort within smart home environments. Future work will focus on integrating energy monitoring, intelligent scheduling, enhanced security features, and machine learning techniques to improve system autonomy and energy efficiency (Khan et al., 2023; Chen et al., 2026).

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