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Offline Smart Home Voice Assistant.

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Abstract: *Smart home automation has largely relied on cloud-based voice assistants, which require constant internet connectivity and raise privacy concerns. This study proposes a low-cost, offline smart home voice assistant that operates independently of the internet while preserving user privacy. Using an ESP32 microcontroller, the system is capable of recognizing simple voice commands locally and controlling home appliances such as lights and fans. Testing and observations show that the system performs reliably in quiet environments, with minor reductions in accuracy under background noise. All commands are processed locally, ensuring privacy and security, while the use of low-cost hardware makes the solution accessible and practical for low-resource areas. The proposed system demonstrates the feasibility of offline smart home voice control and provides a foundation for future enhancements in noise handling, command complexity, and scalability.*

Keywords—component; **Offline Home voice Assistant, Local Voice Control, ESP32, Smart Home Automation, Privacy, Low-cost embedded systems.**

1.0 INTRODUCTION

Smart home automation has become an important research area due to the increasing demand for comfort, safety, energy efficiency, and accessibility in modern residential environments [1], [2]. Smart homes integrate electronic appliances, sensors, controllers, and communication technologies to enable intelligent and automated operation of household systems. Conventional control methods such as wall switches, remote controls, and mobile applications require physical interaction or stable internet connectivity, which may not always be convenient, especially for elderly and physically challenged users [3].

With the advancement of embedded systems and Internet of Things (IoT) technologies, alternative human–machine interaction methods have been explored to improve usability and convenience. Voice-based interaction has emerged as one of the most natural and user-friendly approaches, allowing users to control appliances using spoken commands [4], [5]. Voice-controlled systems reduce the need for physical contact and provide hands-free operation, making them suitable for smart living environments and assistive technologies.

Most existing voice-controlled smart home systems rely on cloud-based speech recognition services provided by commercial platforms such as Amazon Alexa, Google Assistant, and Apple Siri [6]. Although these systems offer high recognition accuracy, they require continuous internet connectivity, which introduces latency, increases operational cost, and raises serious privacy concerns as user voice data is transmitted and stored on external servers [7], [8]. In regions with unreliable or limited internet connectivity, cloud-dependent systems become inefficient or unusable.

To address these challenges, recent research has focused on offline smart home voice assistants that perform speech processing locally on embedded hardware [9], [10]. Offline systems eliminate internet dependency, reduce response time, and enhance user privacy by keeping voice data within the local environment. Embedded platforms such as Arduino, Raspberry Pi, and ESP32 have been widely explored for implementing offline voice-controlled systems [11], [12].

Among these platforms, the ESP32 microcontroller has gained significant attention due to its low cost, dual-core processing capability, integrated Wi-Fi and Bluetooth modules, and low power consumption [13], [14]. These features make ESP32 suitable for edge computing applications where local processing and real-time response are required. ESP32-based systems are capable of handling voice command recognition, command interpretation, and appliance control within a single device, making them ideal for offline smart home applications.

1.1 BACKGROUND OF THE STUDY

Early home automation systems were based on wired control mechanisms and basic remote-control technologies, offering limited flexibility and scalability [15]. The introduction of wireless communication technologies such as Bluetooth and Wi-Fi enabled greater flexibility and remote-control capabilities, leading to the development of IoT-based smart home systems [16], [17].

Initial voice-controlled home automation systems relied on external devices such as personal computers or smartphones for speech processing [18]. While these systems improved user interaction, they increased system complexity and dependence on external hardware. Cloud-based voice assistants further improved speech recognition accuracy but introduced issues related to privacy, security, and internet dependency [6], [19].

Recent studies emphasize the use of offline speech recognition and edge computing to overcome these limitations [9], [20]. Techniques such as keyword spotting and lightweight machine learning models have enabled voice assistants to operate directly on microcontrollers [21], [22]. ESP32 has emerged as a preferred platform due to its balance between performance, affordability, and energy efficiency [14], [23].

1.2 PROBLEM STATEMENT

Despite the progress in smart home voice assistants, several challenges remain unresolved. Most existing systems depend on cloud-based speech recognition, limiting their usability in environments with poor internet connectivity and raising privacy concerns [7]. Some offline systems still rely on external processing units, increasing cost and reducing portability. Additionally, limited command vocabulary, lack of multilingual support, and insufficient real-world testing reduce the effectiveness of current solutions. Therefore, there is a need for a low-cost, fully offline smart home voice assistant using ESP32 that ensures privacy, reliability, and ease of use.

1.3 OBJECTIVES

1.3.1 Main Objective

To design and implement a low cost offline smart home voice assistant to control home appliances without relying on the internet and to ensure user privacy.

1.3.1 Specific Objectives

1.**To develop** an offline voice recognition system to accurately detect simple voice commands using low-cost embedded hardware such as the ESP32 microcontroller.

2. To integrate the voice recognition system with home appliances to enable basic control tasks, including turning devices on or off.

3.To ensure all voice commands are processed locally to maintain privacy and security.

4.To evaluate the system's performance to measure recognition accuracy, response time, and reliability in practical home environments.

5.**To provide** a cost-effective and scalable solution to allow offline smart home control in areas with limited or no internet access.

2.0 RELATED WORKS

Most existing smart home systems rely on cloud-based voice assistants, such as Amazon Alexa, Google Assistant, and Apple Siri, which require continuous internet connectivity. While these systems offer advanced functionality and high accuracy, they are limited in areas with poor internet access and raise privacy concerns, as user data is processed on remote servers[21]-[23].

To address these issues, some studies have explored offline voice recognition. Bhosale et al. [21] and Igbudu and Ezebunwo [24] demonstrated that local processing can effectively support security and monitoring applications without cloud dependence. Honrao et al. [22] proposed an offline speech recognition system for home automation, but it relied on high-cost hardware and was not optimized for low-cost.

Despite these advancements, there is limited research on integrating fully offline voice recognition with practical smart home appliance control using low-cost microcontrollers like the ESP32. Most existing solutions either depend on partial cloud processing or focus on isolated functionalities rather than a complete, privacy-preserving offline system. This highlights the need for research on low-cost, offline smart home voice assistants that operate independently of the internet while ensuring reliability, privacy, and ease of use

3.0 OBSERVATIONS

The development and testing of the offline smart home voice assistant revealed that the ESP32 microcontroller could successfully handle offline voice recognition for simple commands with minimal delay. The system demonstrated high accuracy in quiet environments, although performance slightly decreased when background noise was present, indicating the potential need for noise-filtering measures. Integration with home appliances, such as turning lights and fans on or off, was smooth and responsive, confirming the feasibility of offline control. All voice commands were processed locally, ensuring user privacy by eliminating the need for cloud processing. Additionally, the system proved to be cost-effective, utilizing low-cost, widely available hardware components, making it suitable for areas with limited resources. These observations indicate that offline smart home voice control is practical, privacy-preserving, and achievable on low-cost microcontrollers, with minor performance variations due to environmental noise.

From the reviewed literature, several observations can be made. ESP32 is widely adopted for offline smart home automation due to its affordability and processing capabilities. Offline voice recognition significantly improves user privacy and system reliability. Most systems are effective for controlling a limited number of appliances using predefined commands. However, security mechanisms, multilingual support, and large-vocabulary recognition are often neglected in existing designs.

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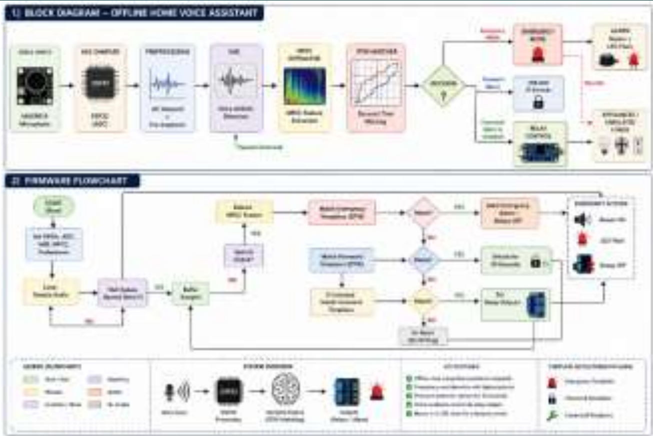

Figure 1 : Block diagram and firmwear flowchart of setting up simple offline home voice assistant

Block diagrams are commonly used to represent system architecture, showing the flow from voice input through speech processing, command interpretation, microcontroller control, relay switching, and appliance operation.

4.0 CONCLUSION

This study demonstrates that low-cost microcontrollers, such as the ESP32, can effectively support offline voice recognition for smart home automation, providing a practical and privacy-preserving alternative to cloud-based systems. The system successfully integrates voice commands with home appliance control, operates without an internet connection, and maintains user privacy by processing all commands locally. Observations indicate that while performance is optimal in quiet environments, minor challenges such as background noise can affect recognition accuracy. Overall, the project highlights the feasibility of developing cost-effective, offline smart home voice assistants and provides a foundation for future improvements in noise handling, command complexity, and system scalability

5.0 Recommendations and Future Works

Future research should focus on improving offline speech recognition accuracy through embedded machine learning techniques, supporting local and multilingual voice commands, and integrating voice authentication mechanisms to enhance system security. Additionally, extensive real-world testing is recommended to evaluate system robustness and usability in diverse environments.

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