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Retrofitting Legacy Homes With AI-Based Offline Voice Control

Supriya Telsang[1], Chinmay Joshi[2], Kapil Joshi[3], Ojas Joshi[4], Aditya Dhule[5]
[1,2,3,4,5]*Department of Computer Engineering, Vishwakarma Institute of Technology, Pune, India*

***Abstract*—Numerous current smart-home systems rely on proprietary ecosystems and cloud-based voice assistants, which necessitate constant internet connectivity and frequently require replacing outdated appliances or electrical infrastructure. These restrictions raise issues with latency, dependability, and user privacy and make it challenging to implement such systems in older homes. A retrofit-focused offline voice-controlled home automation system that can function without internet access or specific smart appliances is presented in this paper. The suggested system makes use of an AI speech recognition module that can recognize commands and identify keywords on-device, allowing for direct voice control of household appliances using pre-programmed commands. Relay-based control interfaces are used in the architecture's integration with current electrical switchboards to automate traditional appliances without the need for centralized hubs or rewiring. Four household loads, such as lighting and fan circuits, were controlled by a prototype implementation. An average command recognition accuracy of roughly 90% with a response latency of 100–150 MS was attained in an experimental evaluation conducted in a typical indoor setting. While recognition accuracy declined for far-field voice input beyond about 10 m in noisy environments, performance remained consistent under typical household indoor conditions. The findings show that offline voice-controlled retrofitting of legacy home infrastructure is feasible.**

***Index Terms*—retrofit, smart homes, offline, voice recognition, IoT, automation**

I. INTRODUCTION

Smart-home technologies have transformed the way users interact with appliances an indoors environment. One of the emerging technologies include voice controlled systems to operate appliances through natural speech. Popular platforms like Alexa and other cloud-based voice assistants have made such automation widely accessible, allowing users to control lighting, cooling and more through centralized smart home ecosystems[1].

Despite their widespread use, these technologies rely heavily on cloud-based recognition modules and continuous internet connectivity. In such systems, the user's voice is transmitted to decentralized servers for processing and sent back as a control signal. Such an architecture has many limitations like increased latency, no working without internet connectivity and potential privacy related concerns regarding audio data being sent to external servers. Furthermore, many commercial smart-home solutions require users to replace their existing system(wirings and appliances) with the one fitted to the company's need thus increasing installation cost drastically.

Legacy Homes where architecture of the building is often old have problems with such installation; thus retrofitting them with retrofit-friendly automation system with offline control and keeping existing electrical infrastructure is the smartest solution possible[2]. Recent developments in edge-based processing and embedded speech recognition makes it possible to perform the tasks of a smart home automation system without the need for cloud connectivity thanks to compact hardware modules that can perform keyword spotting and command recognition directly on-device. These systems can operate in offline environments while lowering latency, increasing reliability, and protecting user privacy by processing speech locally.

An offline voice-controlled home automation system created especially for retrofitting current residential electrical infrastructure is presented in this paper. Conventional appliances can be operated with pre-programmed voice commands thanks to the suggested system's embedded speech recognition module, which can detect keywords and execute commands on-device. Relay-based control interfaces allow the system to interface with current switchboards, allowing automation without the need to install centralized hubs or replace appliances.

II. LITERATUERE REVIEW

Recent advancements in smart-home automation have focused on using voice interfaces for easier appliance control. Many commercial solutions depend on cloud-based speech recognition systems like Amazon Alexa or Google Assistant. These systems process voice commands remotely and then send signals to household devices. While these systems offer flexibility, they face challenges with latency, network dependency, and privacy because they continuously transmit audio data to remote servers.

Several studies have looked into offline speech recognition techniques to tackle these issues. Froiz-Míguez et al. developed an edge-based voice recognition system that can perform command recognition on embedded platforms without needing cloud connectivity. Their implementation showed reliable command detection using compact automatic speech recognition models on resource-limited devices [3]. Similarly, Huang et al. presented a decentralized architecture for voice-controlled smart homes, incorporating local keyword spotting in individual devices to cut down on latency and energy use [4].

Other research has examined offline smart-home frameworks. The HomeIO system combines wake-word detection, speech-to-text processing, and natural language understanding to support privacy-friendly home automation [5]. Although this method removes the need for the cloud, it relies on a relatively powerful central processing unit, which raises the system’s cost and complexity.

Earlier offline speech-based automation systems used traditional speech recognition techniques like Hidden Markov Models (HMM) on embedded computers [3]. While these systems proved that offline voice control is possible, they often needed a lot of computational resources and had limited command vocabularies.

Some researchers have looked at microcontroller-based systems for affordable home automation. Irugalbandara et al. created a voice-controlled system using the EasyVR speech recognition module to manage electrical appliances. Although this system allowed for offline command recognition, it only supported a small command set and needed specialized hardware. Other studies have paired Arduino-based control systems with smartphone-based speech recognition interfaces [7] such as Bluetooth or more [6]. While these setups simplify speech processing, they depend on external devices, which makes them less suitable for standalone embedded systems.

More recent work has examined offline speech recognition modules like the AI Thinker VC02 for embedded voice control applications. Systems using the VC02 module have shown reliable recognition of predefined commands, with response times usually between 250 to 500 ms[8]. However, many of these implementations primarily focus on basic appliance control and do not consider how to scale to existing household infrastructure.

Other automation frameworks use various wireless communication technologies like Bluetooth, ZigBee, and Wi-Fi to allow for multi-room device control. While these designs offer flexible connectivity, they often rely on centralized gateways or cloud speech recognition services. Additionally, mobile-assisted home automation systems using local natural language processing have been suggested, but they depend heavily on smartphones for interactions [9][10].

Moreover, several Arduino-based voice control systems have been created for straightforward appliance switching tasks [7]. Although these designs show the practicality of speech-based control, many need dedicated smart appliances or external processing platforms.

Despite these advancements, a major gap remains in developing retrofit-friendly, fully offline voice-controlled automation systems that can seamlessly integrate into existing household wiring. Most current solutions depend on centralized processors, smartphone interfaces, or internet access. The system proposed in this work aims to fill this gap by allowing offline voice-controlled automation using embedded speech recognition modules capable of managing multiple appliances while connecting to traditional electrical switchboards.

III. SYSTEM ARCHITECTURE

A. *System Overview*

In the proposed design, a single embedded voice recognition module can control multiple household appliances using predefined voice commands. The user's voice is captured, transmitted to the module, which sends a digital signal via GPIO pin which is mapped to a specific appliance based on appliance type via a relay driver circuit.

When the signal is passed from the GPIO pin, the relay switches the power supply to the corresponding device(light, fan etc) to be controlled via the voice command. As the single module has 20+ GPIO pins, several devices can be controlled via a single module. The use of relay-based switching allows the system to integrate with existing electrical switchboards properly easily enough with a technician.

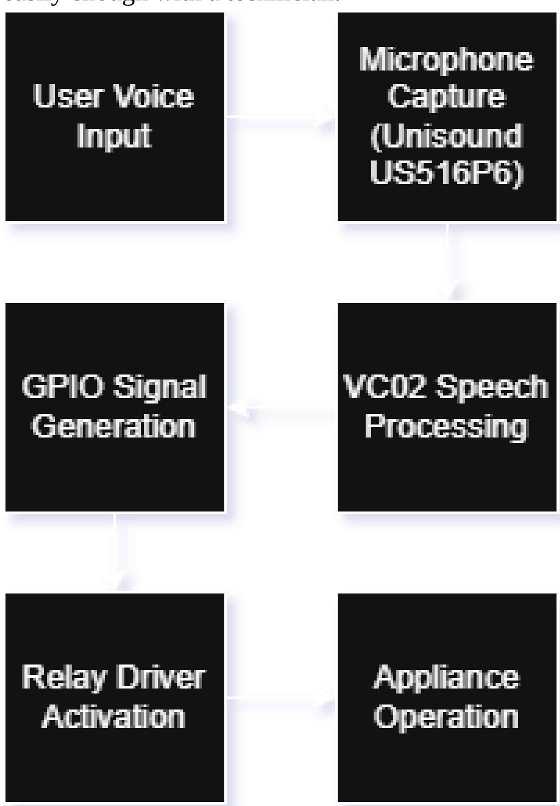

Fig. 1. Flowchart of proposed system

B. Voice Recognition and Control Module

The main processing part of the proposed system is the AI Thinker VC-02 offline speech recognition module. This module uses the Unisound US516P6 voice processing chip. It is made for embedded voice control applications and allows for complete offline speech recognition without needing cloud connectivity[11]. By spotting keywords and recognizing commands directly on the device, the system can respond to voice commands without sending audio data to external servers.

The US516P6 processor is built on a 32-bit RISC architecture that runs at 240 MHz. It includes special digital signal processing features tailored for speech recognition. The processor also has a floating-point unit (FPU) and a Fast Fourier Transform (FFT) accelerator, which improves how efficiently it processes audio signals and extracts acoustic features necessary for recognizing commands.

The VC-02 module has 242 KB of on-chip SRAM and 2 MB of internal flash memory. This memory stores the firmware, acoustic models, and a set of predefined commands for offline recognition. The module can recognize up to 150 voice commands stored locally, allowing for control of multiple appliances within one system.

Voice input is captured using a microphone connected to the module's audio interface. The speech recognition engine processes this input to identify predefined commands. When a command is recognized, the module sends a control signal through its General-Purpose Input/Output (GPIO) interface. These GPIO outputs connect to relay driver circuits that manage the power supply to different appliances. With several GPIO pins available, a single VC-02 module can control multiple household devices while remaining efficient and fully offline.

C. Hardware Integration and Safety

The hardware design guarantees safe interaction between the low-voltage control electronics and the high-voltage household electrical system. The VC-02 module operates with a low-voltage DC supply of about 3.6 to 5 V. This supply powers the built-in speech recognition processor and the related control circuitry. This control unit works independently from the appliance power circuit. This setup ensures a safe separation between the processing and switching stages.

To connect the voice recognition module with household appliances, electromechanical relay modules serve as switching devices. Each appliance connects to a specific relay channel that controls the AC power line supplying the device. When the VC-02 module picks up a valid voice command, it changes the state of the corresponding GPIO pin and activates the relay driver circuit. The relay then switches the appliance between ON and OFF states by controlling the link between the live power line and the load.

Electrical isolation between the control circuit and the high-voltage load is provided by relay modules with optocouplers and transistor driver stages. These components stop high-voltage spikes from reaching the low-voltage control electronics. Flyback diodes are also used across relay coils to reduce back electromotive force created during switching. This protects the GPIO outputs of the control module and increases system reliability.

The modular design lets the control circuitry integrate into existing switchboards or appliance control panels without needing major changes to the electrical setup. By using relay-based switching and low-voltage control interfaces, the system allows easy retrofitting of regular household appliances while ensuring safe electrical operation.

IV. METHODOLOGY

This section focuses on the setup of the ai thinker VC 02 module via SDK and the hardware setup for this implementation. note sections A-D below for more information on proofreading, spelling and grammar.

A. Voice Command Configuration

Voice command recognition in the proposed system is configured using the development tools provided by AI Thinker for the VC-02 speech recognition module. The command vocabulary is defined through the configuration interface available on the AI Thinker development platform.

Predefined voice commands corresponding to appliance control actions are specified within the configuration tool. Each command phrase is mapped to a particular General-Purpose Input/Output (GPIO) pin of the VC-02 module. For example, commands associated with switching appliances ON or OFF are linked to the GPIO outputs connected to the relay channels controlling the respective devices.

Once the command vocabulary and GPIO mappings are defined, the configuration is compiled using the platform’s development environment. The compiled configuration package is then downloaded and uploaded to the VC-02 module, where it is stored in the module’s internal flash memory. This configuration enables the module to perform offline keyword detection and command recognition without requiring internet connectivity.

B. Experimental Setup

A prototype method was created to assess the given system. The setup included the VC-02 speech recognition module, the built in microphone of VC-02 for capturing user voice input, and a relay driver module connected to the module’s GPIO outputs.

4 household appliances were linked to the relay channels, 2 lights and 1 fan (like a regulator switch). Each appliance was assigned to a specific GPIO output of the VC-02 module. When the system recognized a specific voice command, it activated the corresponding GPIO signal, which switched on the relay driver circuit, supplying power to the connected appliance.

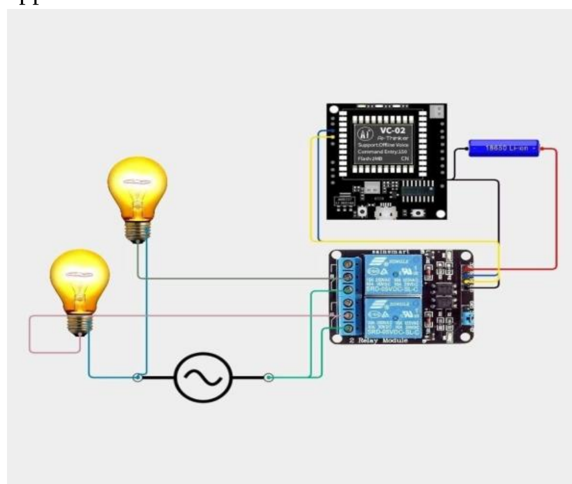

Fig. 2. Circuit Diagram for Experimental Setup

The hardware setup used in the prototype is shown in Fig. 2. Here, The VC-02 module connects to the relay module through its GPIO outputs, while the relay module controls the AC power supply to the appliances. This setup allows multiple devices to be managed using one voice recognition unit.

The system was tested in an indoor and outdoor environment. Users issued voice commands from various distances from the microphone to check system performance in real conditions. Tests were performed in normal indoor environments and with background noise to see how it affected command recognition accuracy.

During testing, the response time between issuing a voice command and switching the appliance was noted. The results from these experiments are presented and discussed in the next section.

V. RESULTS AND DISCUSSION

The performance of the proposed system was evaluated and the following results have been drawn based on the experimental setup.

Table I. Command-wise Recognition Performance

Command	Attempts	Successful Detection	Accuracy
LIGHT 1 ON	20	18	90%
LIGHT 1 OFF	20	18	90%
LIGHT 2 ON	20	19	95%
LIGHT 2 OFF	20	18	90%

From Table I, it can be inferred that the accuracy of the system is ~90%. Minor variations can be accounted for with human error such as difference in pronunciations. The testing for the results of Table 1 were done in an indoors environment with low noise and at a distance of 2 meters.

Table II. Accuracy and Distance Comparison

Distance(in meters)	Accuracy	Observation
1-2m	~90%	Highly Reliable
3-5m	~88-90%	Highly Reliable
6-8,	~75-80%	Slight Degradation
~10m	~65-70%	Reduced Reliability

The results in table II show the given system performs well upto 5m and slight degradation in performance can be seen from 5m onwards. The response delay(latency) is minimal and acceptable for real time usage.

Table III. Overall Analysis

Parameter	Value
Total appliances tested	2 (4 with sdk)
Command Vocabulary	4(8 with sdk)
Recognition Type	Offline Keyword Spotting
Control Interface	GPIO based relay switching
Deployment Environment	Indoors preferred(Outdoors doable)
Internet	Not Required

Overall, the system showed stable and reliable operation in normal indoor conditions while remaining completely independent of internet connectivity. The results emphasize the usefulness of offline voice recognition for upgrading current household systems.

The performance characteristics show that the proposed system is a good fit for practical use in various IoT smart home applications. It has high recognition accuracy in typical indoor conditions and works reliably within a range of up to 5 m. This makes it ideal for residential automation, especially for controlling lighting and small appliances. The system can operate without internet connectivity, which is beneficial in rural areas or places with low connectivity where cloud-based IoT solutions often fail. Also, the hands-free voice control feature can help elderly or disabled users. The compact size of the VC-02 module allows for easy integration and installation in existing electrical systems. Its retrofit-friendly design also makes it easy to adopt in homes, offices, and small environments without needing to replace existing infrastructure.

VI. CONCLUSION

An offline voice-controlled automation system for retrofitting current electrical infrastructure in Internet of Things-based smart home environments was presented in this paper. The suggested system does not require cloud connectivity or specialized smart appliances because it uses an embedded speech recognition module to carry out on-device keyword detection and command execution. Through GPIO-based relay switching, the architecture makes it possible to control numerous appliances with a single module, enabling smooth integration with traditional switchboards.

According to experimental evaluation, the system performs reliably within a range of up to 5 m and achieves an average command recognition accuracy of about 90% under typical indoor conditions. The system is completely offline and offers a practical and responsive voice-based control solution, especially in settings with spotty or inconsistent internet connectivity.

The findings demonstrate the potential of small, embedded voice recognition modules to enable affordable, privacy-preserving Internet of Things-based smart home solutions. The suggested method shows that legacy infrastructure can be successfully upgraded with little change, increasing the scalability and accessibility of smart home functionality.

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