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Offline Bilingual Arabic–English Voice-Controlled Smart Home Automation Using Embedded Hardware and RF Communication

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ABSTRACT

This paper provides the design, implementation, and experimental assessment of an offline bilingual Arabic-English voice-controlled smart home automation system based on embedded hardware and radio-frequency (RF) communication. The given system uses an Arduino-based master-slave architecture, in which local speech recognition is realized with the help of the Elechouse Voice Recognition Module V3, and control commands being sent via HC-12 RF modules with 433 MHz frequency. In contrast to cloud-based voice assistants, all speech processing goes locally, which means that the user privacy is guaranteed and low-latency response is also provided. The system is capable of Arabic and English voice recognition and operating domestic appliances using optocoupler-isolated relay circuits. The experimental performance of RF communication in indoor settings has shown stable communications up to a range of 60m, end to end response latency of less than 300ms and command recognition accuracy of between 85 and 95 percent per command, and a total average command recognition accuracy of 90 percent under low noise conditions. Under high ambient noise, the performance is degraded, which demonstrates the weakness of template-based speech recognition. The findings suggest that offline bilingual voice interfaces used with low-power RF communication can offer a viable, privacy-sensitive solution to small-scale automation of the smart home as well as a platform upon which noise-resistant on-device learning algorithms will be implemented in future applications.

1. Introduction

Smart house technologies continue to expand because of the presence of microcontrollers of low cost, wireless modules of efficiency and user interfaces that are flexible. Voice-based interaction is a familiar usage of the control mechanism since it can be operated hands free and directly activate the device. The advanced features of commercial cloud-based systems like Amazon Alexa and Google Assistant have certain issues connected with privacy, latency, and network performance as they rely on remote servers [1,2,3].

The use of offline speech recognition solves these problems by computing all the commands on-site. Embedded systems based on dedicated hardware like Elechouse V3 or LD3320 modules can provide high responsiveness to the small series of commands, but they are prone to noise in the environment and change in the speaker [4,5,6,7,8,9]. A number of recent articles have discussed the use of TinyML to recognize key words and the use of compressed neural networks to recognise words with greater versatility. [10,11,12].

Reliability of smart home is affected by wireless communication. Wi Fi and Bluetooth are short range connectivity with generally increased power consumption or more complicated set up. RF modules like the HC 12 have a longer communication range and they consume less power and have simple serial interfacing that can be easily applied to Arduino based system [13,14,15]. The hybrid cloud RF architectures and secure multi standard networks have as well been discussed [16,17,18].

The majority of embedded speech systems are directed at English [19,20,21]. Embedded systems have fewer examples of Arabic speech recognition than English because of the phonetic diversity and dialectal diversity of the language. Research indicates that searching Arabic keywords in the small hardware is usually characterized by lower resilience and less vocabulary [22,23,24]. Multilingual interfaces enhance usability within a wide range of settings but are still restricted within regional literature [25]. This project combines both the offline Arabic and English voice commands and the long-range RF communication system to a single low cost. A relay interface based on an optocoupler is used to implement isolated switching, and the design is tested in a practical environment at home. The system will be developed to ensure that it offers an accessible and privacy conscious smart home control system that does not require Internet services.

Although there is a growing number of literature on voice-controlled smart home systems, the current research usually focuses on a smaller number of the necessary system properties. Cloud-based solutions are highly recognized but need to be constantly connected to the internet, which creates issues associated with privacy, latency, and network dependency [4,5,6,7,8,9]. The embedded speech recognition system is applied concurrently with offline speech recognition to mitigate these problems but is frequently restricted to English operation only and limited communication technology like Bluetooth which constrain deployment capabilities [13,14,15]. Conversely, studies on Arabic speech recognition of embedded systems are mainly done on dataset development or benchmarking and lacks the incorporation of hardwar based smart home control system [22,23,24]. The authors believe that to the best of their knowledge, there are no integrated systems which would provide at the same time offline speech processing, bilingual Arabic-English command support and long-range RF-based communication in one embedded smart home automation system. This gap is covered in this work, where the authors present and experimentally assess an offline bilingual smart home system, which integrates the local template-based speech recognition with HC-12 RF communication with the focus on the preservation of privacy and practical implementation in the indoor environment.

2. Contributions and Novelty

This paper provides a practical system level research which attempts to overcome known impractical constraints in current voice controlled smart home applications. The key findings of this paper will include the following:

1. Integrated offline bilingual voice control: The paper describes a fully offline environment of a smart home automation system with bilingual Arabic–English command support eliminating dependence on cloud services and preserving the privacy of the user.
2. Bilingual speech recognition in combination with long-range RF communication: The proposed architecture is non-comparable to current systems that use limited short-range wireless services, with the proposed architecture, enabling reliable indoor control of large areas via HC-12 RF communication and local voice recognition.
3. Experimental analysis in realistic indoor settings: The system is experimentally tested in realistic indoor settings, where accuracy of command recognition, range of communication, end-to-end latency, and power consumption are

reported, as well as the degradation of the performance of the system under varying ambient noises.

4. Limitations of template-based recognition to bilingual operation analyzed: The work, by controlled experiment, shows the sensitivity of template based speech recognition to noises and speaker dependency during bilingual operation, and this gives experimental motiviation to the future on-device extensions of learning based systems.

Instead of suggesting a new speech recognition algorithm, the presented paper will offer a reproducible and experimentally validated embedded platform that illustrates how offline bilingual voice interaction and long-range RF communications can be integrated into one smart home automation platform.

3. System Design and Implementation

The system is characterized by the master node that is tasked with speech recognition and RF transmission, and the slave nodes that are tasked with receiving commands and switching electrical loads.

Figure 1 shows the flow of operations of the proposed offline bilingual voice-controlled smart home system is organized into a master node (sender) and a slave node (receiver). Initially, at the master node, the system power-on, and system initialization (whereby communication interfaces are configured) are initiated. The system then goes to the listening mode where the captured sound is constantly checked. In case there is no suitable voice command identified, the system goes to the listening state once again. Upon successful recognition of a command, the respective command identifier is determined, an RF data packet is built and the packet sent to the slave node through the HC-12 module.

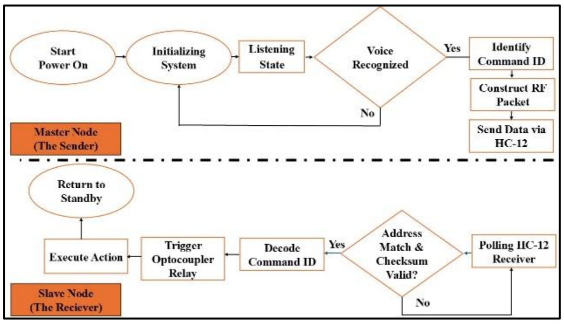

Fig. 1. Flowchart for bilingual voice command recognition and RF-based relay control.

The HC-12 receiver on the slave node keeps on polling to receive RF data. When the packets are received, the address and checksum are checked. In case of failure of validation, the system goes into polling state. Once a valid packet is detected, the command identifier is decoded and the optocoupler-isolated relay activated and the relevant action is performed. Once the execution is done, the slave node goes again to the standby state awaiting the next command.

3.1. Voice Recognition Module

The Elechouse voice recognition module V3 is a template based speech recognition without requiring additional signal processing. In this piece of work two Arabic commands and four English commands were trained as a common on/off control action representation in a smart home environment. The commands were repeated multiple times throughout training in order to enhance recognition stability.

The module allows a maximum of 80 voice templates to be stored in a non-volatile storage; it can however not load any more than seven commands in the active recognizer at one time. commands out this working set are not considered during recognition. As part of the experimental system, six working commands were carefully chosen in order to ensure consistent bilingual function, and to prevent the overwriting of templates. Trained set of commands were used, and in the controlled indoor conditions, an overall recognition accuracy of 90 was obtained as reported in Table 1.

Table 1. Voice recognition performance in Bilingual.

Command	Language	Trials (Attempts)	Successful Execution	Success Rate (%)
Light On	English	20	19	95 %
Light Off	English	20	18	90 %
تشغيل (On)	Arabic	20	18	90 %
ايقاف (Off)	Arabic	20	17	85 %
Total/ Avg	-------	80	72	90 %

The command vocabulary size and the amount of memory used increases with the number of templates stored, whilst the recognition accuracy can be degraded due to the presence of acoustic similarity between templates, especially in a bilingual situation where the overlapping phonetic features is existed. In addition, scaling of the system is hindered by the need to load and offload command groups dynamically.

Since a small set of commands can be active during execution. These characteristics reflect inherent limitations of template-based recognition and encourage future improvements of template based recognition to speaker-independent and noise-roboust on-device learning features.

Table 1 has shown recognition results that were obtained with only one trained speaker, and the system is speaker-dependent. Training and testing were conducted on the same speaker with testing being done after the training phase was over. There was no cross-speaker or speaker independent assessment. The reported success rates, thus, denote recognition performance under controlled condition are used and represent an upper-bound estimate of the accuracy that can be obtained by the trained user. The protocol was chosen to evaluate the baseline system performance instead of general purpose speech recognition performance.

3.2. RF Communication

Master to slave node communication is done using HC-12 radio-frequency Transceiver at 433 MHz. Once a valid voice command has been identified at the master node, data packet with the destination address, command identifier and a checksum is sent wirelessly to the respective slave node. Following successful reception and validation of the command, the slave node decodes the command, enabling the appropriate optocoupler-isolated relay to operate the electrical load.

The range testing was done indoors, in a reinforced-concrete structure that had two levels and a series of confined rooms and corridors. The master node was stationary in one of the rooms on the first floor and the slave node was placed successively in various rooms on both floors to test the reliability of communications under normal obstructions of indoor environment. Constant RF communication was obtained in all the locations tested in the first floor. The second floor also maintained stable operation of the majority of locations, however, the loss of communication in the farthest distant tested room was detected, which could be attributed to the fact that signals are attenuated when the vertical separation is greater, and buildings act as obstacles.

Both HC-12 modules were run in default mode and with the standard quarter-wave wire antennas, which were mounted vertically with a height of about 1.2 m above the ground. External amplifiers and directional antennas were also not used. In this case, the distance of the most reliable indoors communication was about 60 m.

Arduino Uno microcontrollers are used as logic controllers on both the master and the slave nodes. The master keeps listening to identified messages sent by the Elechouse module. Once the command has been detected, the master will encode and send a packet to the correct slave node. By interpreting the packet, the slave switches on or off its relay in response.

3.3. Power Supply and Circuit Design

An external power supply of 5 V DC is used to power the system. Relay modules have optocouplers that separate the microcontroller and electrical noise that is produced during switching. Fig. 2 reports physical implementation, comprising the master node which includes voice recognizing module, LCD display, and HC-12 transceiver and two slave nodes to control a light bulb and a fan with the help of relay modules.

Fig. 2. The physical implementation of bi-lingual smart house control system.

3.4. Hardware Components Table

Table 2 presents the key elements of hardware along with their electrical ratings and primary purposes of application added in the proposed system to provide a brief overview of the components. In our experiment this data is informed with the datasheet specification and setup. The table highlights the operation of the master and slave node including voltage, current load and the working of all elements of the system design.

Table 2. Components of hardware utilized in the slave and master node.

Component	Voltage	Current	Node Role	Notes
Arduino Uno	5 V	50 mA	Master & Slave	Central logic unit for packet encoding/ decoding.
Elechouse V3	5 V	20 mA	Master Only	Bilingual voice recognition and template matching.
HC-12	3.3–5 V	15 mA	Master & Slave	Long-range RF communication at 433 MHz.
Relay Module	5 V	70 mA	Slave Only	Optocoupler-isolated switching of electrical loads.
LCD 16x2	5 V	20 mA	Master Only	Visual feedback for command execution status.

4. Results and Evaluation

To evaluate the behavior of the system in a multi-device set up, two slave nodes were tested one with a controlling load of a lighting load and the other controlling a fan load. The experiments were carried out in indoor environments at different levels of ambient noise levels. In each test, the trained user used predefined English commands of the light (Light On, Light Off) and Arabic commands (تشغيل ، إيقاف). Upon receiving a command, the relays were actuated in accordance with the issued command, indicating successful execution. Seamless RF communication was ensured over the range of the tests and no packet was lost at the low noise condition. The recognition success rate was reduced with increased ambient noise and in certain instances a series of attempts were needed in order to perform the correct actuation. These findings reveal that the acoustic conditions are the main limiting factor to system performance rather than the RF link reliability.

4.1. Performance Evaluation

Indoor trials with repeated sessions that assessed the recognition reliability , the stability of RF communication and latency of the response were used to evaluate the performance of the proposed system. In both test sessions, predefined Arabic and English commands were issued repeatedly and the success was recorded when the related relay state changed accordingly.

Recognition performance remained consistent in the repetitive trials occurred under similar acoustic conditions,. No difference between Arabic and English commands was observed under low background noise. Communication via RF was maintained on the entire tested indoor distance and packet loss was not observed after up to the distance of operation. The delay of voice command and relay activation when a voice command was given was similar throughout the trials and did not show any significant differences with distance.

High ambient noises were mostly related to performance degradation, as opposed to the range of communication or system processing. These findings support the fact that the limitation of system-level performance is primarily the nature of the template-based speech recognition module, with RF transmission and microcontroller processing providing insignificant variability in the conditions of the experiment.

4.2. Observations and Discussion

Experimental work was conducted under various acoustic conditions in the indoor environment in order to determine how ambient noise influences recognition performance. The ambient noise levels were measured with via a smartphone-based sound level application, placing a device about 1 m away with the speaker. The noise reported values are approximate average values of the noise that is monitored prior to the use of voice commands and is intended to be compared, but not strictly described as an acoustic character. There are three conditions, representative that were taken into account: a quiet room, a room with a fan running, and a room with television or music being played. Table 3 reflects the respective success rates of recognition when the conditions are described as follows.

Table 3. System Robustness Under Different Ambient Noise Levels.

Environment	Avg. Noise Level (dB)	Total Trials	Successful Recognitions	Success rate (%)
Quiet Room	30-35 dB	25	24	96 %
Room with Fan On	45-50 dB	25	18	72 %
Room with TV/Music	60-65 dB	25	11	44 %

To also confirm the originality and functionality of the proposed architecture, a comparative analysis was made with the existing smart home automation research available in literature. In brief summary as in Table 4, the proposed system has a unique advantage in terms of privacy and working range. Though some cloud-based designs are very functional, they are still reliant on the internet connection and are prone to latency and loss of data security. Contrarily, this experiment shows a complete offline bilingual performance which is far better than the normal Bluetooth-based system which limits its short distance communication (~10m). With the proposed design option, a stable 60m indoor distance is ensured with the help of the HC-12 RF link and can be used to execute Arabic and English commands on the resource-constrained hardware.

Table 4. Comparison of the Proposed System with Related Smart Home Research.

Reference	Language Support	Speech Processing	Connect-ivity	Offline Operation	Indoor Range
Gondi et al. [1]	English	Embedded (ML-based)	Local / Wired	Yes	Not reported
rugalbandara [4]	English	Cloud-based	Wi-Fi	No	Network-dependent
Ibrahim et al. [7]	English	Template-based	Bluetooth	Yes	~10m
Ghandoura [22]	Arabic	Not applicable (dataset study)	Not applicable	Not applicable	Not evaluated
Proposed System	Arabic and English	Template-based	HC-12 RF	Yes	~60 m

This findings highlight the necessity of standardized pronunciation and the possibility of introduction of TinyML models in the future to enhance noise-resistance in non-controlled setups. In Fig. 3, the sender records the voice input, analyses it, via the voice recognition module and sends it to the Arduino Uno, also encodes the identified command and transmits it using the HC-12 RF module. The receiver interprets the signal, turns on the appropriate relay and operates some connected loads, including a fan or a light bulb.

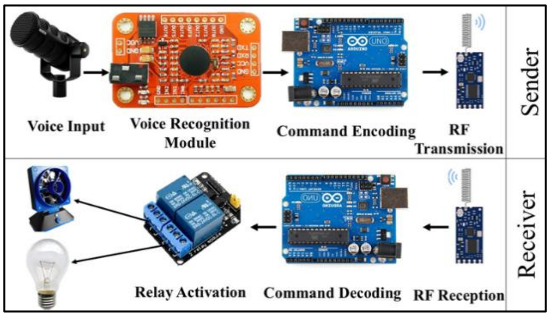

Fig. 1. Block diagram of voice command processing and RF transmission at the receiver node (relay-driven appliance control) by the sender node.

4.3. Communication Range and Latency

The RF HC-12 module utilized offered consistent communication over a 60m radius in an indoor setting without the loss of packets. In contrast to Wi-Fi or Bluetooth, the RF connection was very good at penetrating through household walls as well as using less power. Table 5 will compare these technologies and show that the selected architecture has faster range and more privacy.

Table 5. Comparison of Wireless Technologies for Smart Home Control.

Feature	Proposed (HC-12 RF)	Standard Wi-Fi	Standard Bluetooth
Indoor Range	~60m - 100m	~30m - 50m	~10m
Power Needs	Low (Sub-1GHz)	High	Medium/Low (BLE)
Privacy	High (Offline/Local)	Low (Cloud-based)	High (Local Only)
Complexity	Simple Serial	High (TCP/IP)	Moderate (Pairing)
Internet Required	No	Yes (Usually)	No

Time intervals between relay actuation and voice command issuance were measured repeatedly to determine system latency. The values of latency of each of the test stages in Table 6 were recorded using 20 repeat trials in low-noise indoor environment. The latency ranges reported represent minimum and maximum values whereas the overall end to end latency claculated based on the average response time range. This method was used to describe practical system responsiveness instead of worst-case timing behavior.

4.4. Power Consumption Analysis

The power consumption of both the master and slave nodes were evaluated by measuring the current consumed by the 5 V supply during changing the operating state.

Table 6. System Latency for Local Command Execution.

Test Stage	Description	Measured Delay (ms)
Speech Processing	Time taken by Elechouse V3 to recognize command	150 – 250 ms
Master Logic	Packet encoding and RF preparation	10 – 20 ms
RF Transmission	Data travel time via HC-12 at 433 MHz	5 – 10 ms
Slave Execution	Packet decoding and Relay activation	5 – 15 ms
Total Latency	Total response time from voice to action	170 – 295 ms

Digital DC clamp meter was used to measure the current at a given point by placing around the positive supply conductor where the supply voltage was kept constant. Power values in Table 7 were obtained as the product of current and supply voltage. Measurements were conducted under steady-state conditions during both standby and active relay operating conditions.

Table 7. Current Consumption and Power Rating of Nodes.

Node Type	Operating Voltage (V)	Avg. Current (mA)	Power (mW)
Master Node (Arduino + V3 + HC-12)	5V	~85 mA	425 mW
Slave Node (Standby)	5V	~65 mA	325 mW
Slave Node (Relay Active)	5V	~135 mA	675 mW

5. Conclusion

This paper presented an embedded smart home automation system based on offline bilingual Arabic-English voice recognition and RF communication. The proposed system with no cloud services requirements or network connectivity by implementing speech recognition on a local system by sending the commands to a sub-GHz RF system, which ensures that the system is independent and addressing the privacy and latency issues of a voice-controlled home automation. An experimental assessment revealed that the system is capable of consistent control in bilingual command execution in a common indoor setting with minimal embedded hardware. The findings also demonstrate that RF-based communication reliability is ensured even with the obstruction of indoor conditions, and the general system responsiveness is largely limited by the nature of template-based speech recognition instead of communication or processing latencies. The system has got obvious limitations as well. Performance Speech recognition depends on the speaker, and is sensitive to ambient noise, as well as is limited in scalability by the small number of concurrent voice templates the recognition module supports. Despite these limitations, this approach provides a realistic simulation of trade-offs in a low complex embedded voice interface that is applicable to multiuser or very noisy scenarios.

The future research and development will be directed toward substituting template-based recognition with noise-robust, speaker-independent on-device learning approaches, such as lightweight keyword-spotting models, while preserving offline operation. Additionally, testing with a variety of users, extend indoor layouts, and outdoor environments will confirm the system's robustness and scalability.

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