DESIGN AND IMPLEMENTATION OF AN IoT-BASED SMART HOME MODEL WITH VOICE CONTROL AND ENVIRONMENT-BASED AUTOMATION

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Abstract

This paper presents the design and implementation of an Internet of Things (IoT)-based smart home model that integrates voice control and environment-based automation. The proposed system uses an ESP32 microcontroller as the main IoT communication module and an Arduino Mega 2560 for local hardware control. Several sensors and modules, including a DHT22 temperature-humidity sensor, MQ-4 gas sensor, rain sensor, and RFID authentication module, are integrated to support environmental monitoring, safety detection, and automated device operation.

The system communicates with the E-Ra IoT platform to provide real-time monitoring and remote control through a web-based interface, while voice commands are implemented using Google Assistant. A physical prototype was developed and tested under normal operating conditions. Experimental results show that the system operates reliably and responds quickly to control commands, with an average response time of less than 1 second for basic device operations. The proposed model demonstrates the feasibility of building a low-cost and flexible smart home system suitable for research, educational applications, and small-scale residential environments.

Keywords: ESP32; home automation; internet of things; smart home; voice control.

1. Introduction

The Internet of Things (IoT) has significantly transformed the way electronic devices and sensors interact within residential environments. By enabling interconnected communication between sensors, controllers, and cloud platforms, IoT technologies allow smart home systems to provide automated control, environmental monitoring, and remote device management (Atzori et al., 2010; Kumar & Singh, 2017). These capabilities contribute to improving user convenience, enhancing safety, and optimizing energy consumption in modern households.

In recent years, commercial smart home ecosystems such as Google Home, Amazon Alexa, and Samsung SmartThings have demonstrated the feasibility of integrating voice assistants, cloud services, and intelligent automation into everyday living spaces. These platforms allow users to control appliances through voice commands and mobile applications while supporting various automation scenarios based on environmental data or user behavior (Minoli et al., 2017; Google, 2024). However, commercial solutions typically require proprietary devices, higher installation costs, and integrated infrastructure, which may limit their accessibility in developing regions.

In parallel with commercial developments, academic research has explored the implementation of smart home prototypes using low-cost microcontroller platforms such as Arduino, ESP8266, and ESP32. These platforms provide flexible hardware interfaces and built-in communication capabilities, making them suitable for experimental IoT applications and educational projects (Piyare, 2013; Li et al., 2015). Many existing studies focus on individual functionalities such as lighting control, temperature monitoring, or remote device switching. While these implementations demonstrate the feasibility of IoT-based home automation, they often lack comprehensive integration between voice control, environmental sensing, and centralized monitoring systems.

In the context of developing countries, there is increasing interest in designing smart home models that are affordable, modular, and easy to deploy using widely available hardware components. A system that integrates voice control, environmental automation, and remote monitoring within a unified architecture could provide a practical solution for residential applications while remaining suitable for research and educational purposes.

Motivated by these considerations, this study proposes the design and implementation of an IoT-based smart home system that integrates voice-based control with environment-driven automation using low-cost microcontrollers. The system architecture combines an ESP32 module for IoT communication with an Arduino Mega 2560 for local hardware processing. Multiple sensors and actuators are integrated to enable environmental monitoring, safety detection, and automatic device operation.

The main contributions of this work include:

(i) The design of a modular smart home architecture integrating IoT connectivity, voice control, and environment-based automation.

(ii) The implementation of a physical prototype using low-cost hardware components and an open IoT platform.

(iii) Experimental evaluation of system performance under real operating conditions.

The proposed system aims to provide a practical smart home model that can support future research, teaching activities, and potential real-world deployment.

2. Literature Review

In recent years, the application of the Internet of Things (IoT) in smart home systems has attracted significant attention from both domestic and international research communities (Atzori et al., 2010; Kumar & Singh, 2017). Numerous studies have proposed smart home architectures based on microcontroller platforms such as Arduino, ESP8266, and ESP32, combined with communication protocols including MQTT and HTTP/REST for remote monitoring and control (Piyare, 2013; Li et al., 2015). These studies highlight advantages such as flexibility, low cost, and rapid deployment in residential environments.

At the international level, commercial and semi-commercial smart home ecosystems such as Google Home, Amazon Alexa, and Samsung SmartThings have demonstrated high effectiveness in integrating voice control, context-aware automation, and multi-device connectivity (Minoli et al., 2017; Google, 2024). In parallel, many academic studies have focused on optimizing system architectures, improving communication reliability, and enhancing scalability through IoT and cloud-based solutions (Zanella et al., 2014; Al-Kuwari et al., 2021). However, many of these approaches involve relatively high implementation costs, rely on proprietary hardware platforms, and require complex infrastructures, which may limit their applicability in developing economies.

In Vietnam and among Vietnamese research groups, several studies have also investigated IoT-based smart home solutions. Nguyen et al. (2020) proposed an ECHONET Lite-based IoT platform emphasizing interoperability and secure service deployment in smart home environments. Similarly, Nguyen and Nguyen (2019) developed an IoT-based smart home prototype using the ESP8266 platform for remote monitoring and device control.

These studies demonstrate the growing interest in smart home research within the Vietnamese context, particularly in developing low-cost experimental prototypes and IoT platforms for residential applications.

Furthermore, several recent studies have explored IoT-based smart home prototypes using low-cost microcontrollers and basic automation functions. For example, Iliev et al. (2022) developed an IoT-based home automation system focusing mainly on remote lighting control and environmental monitoring. Similarly, Irugalbandara et al. (2023) implemented a smart home prototype using ESP8266 with mobile application control; however, the system did not integrate voice control or environment-based automation. Esposito et al. (2023) introduced a voice-assisted smart home model using a virtual assistant platform, but the implementation primarily focused on voice command interaction and lacked integration with multiple environmental sensors and automated control mechanisms.

Nevertheless, many existing implementations still primarily focus on individual functionalities such as remote switching or environmental monitoring. The integrated combination of voice control, sensor-driven automation, and centralized real-time monitoring within a unified and low-cost smart home architecture remains relatively underexplored in the existing literature.

Table 1. Comparis

on of the proposed smart home system with related works

Study	Voice control	Env. automation	Prototype	Cost focus
Iliev et al. (2022)	No	Yes	Yes	Medium
Irugalbandara et al. (2023)	No	Partial	Yes	Low
Esposito et al. (2023)	Yes	No	Yes	Medium
Nguyen & Nguyen (2019)	No	Partial	Yes	Low
This work	Yes	Yes	Yes	Low

Source: Iliev et al. (2022), Irugalbandara et al. (2023), Esposito et al. (2023), and Nguyen & Nguyen (2019).

3. Proposed system model

3.1. Overall system architecture

The smart home system is designed using a centralized IoT architecture, in which the ESP32 acts as the main controller, providing Wi-Fi connectivity and communication with the IoT platform (Espressif Systems, 2023).

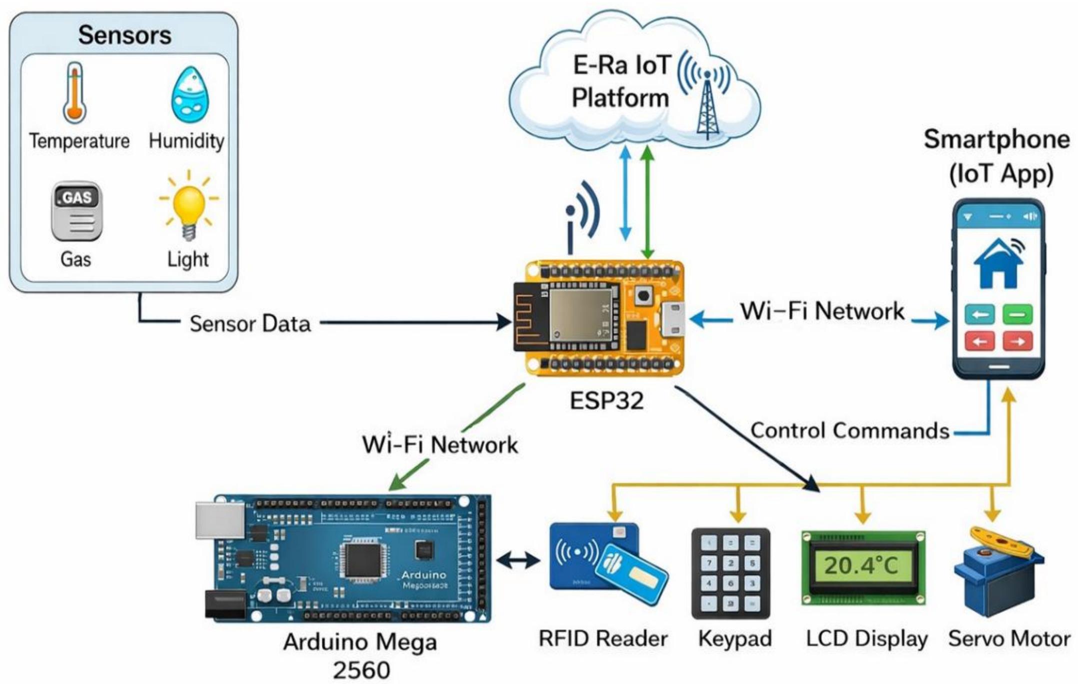

Figure 1. Overall architecture of the proposed smart home system

Source: Authors, 2025

ESP32 collects data from environmental sensors and transmits it to the E-Ra IoT Platform, while also receiving control commands from users. The Arduino Mega 2560 handles local processing tasks such as RFID authentication, keypad input, LCD display, and servo motor control (Arduino, 2023). The combination of ESP32 and Arduino Mega 2560 is selected to separate network communication tasks from local hardware control, improving system stability and scalability.

3.2. Control algorithm flowcharts

Control algorithms are designed to ensure system stability and fast response. Environment-based automation logic allows the system to automatically react to sensor data, such as gas leakage detection as shown in Fig. 2, and rain-based drying rack control, reducing user dependency and improving safety (Piyare, 2013).

The smart lighting control flowchart, as well as the automatic door and clothes rack control flowcharts, are similar to the gas leakage detection and safety alert flowchart.

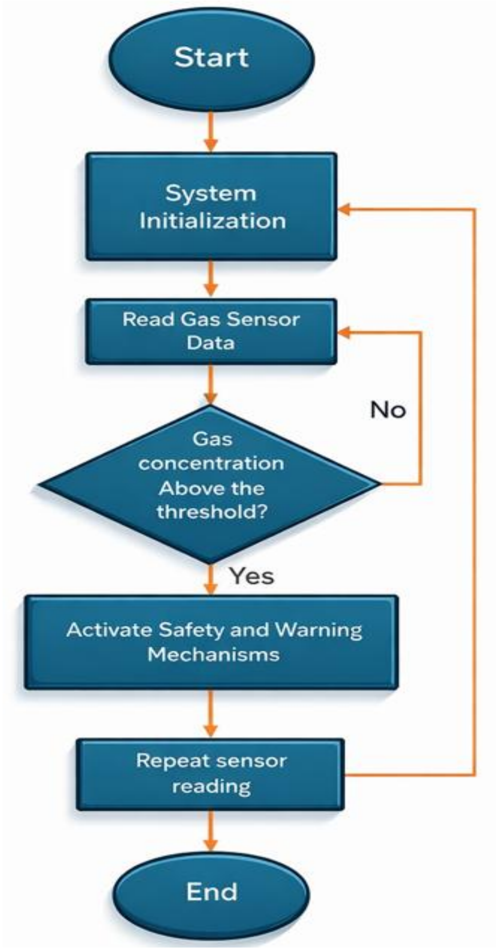

Figure 2. Flowchart of gas leakage detection and safety alert algorithm

Source: Authors, 2025

3.3. Hardware design

The system employs major hardware components including ESP32, Arduino Mega 2560, an 8-channel relay module, DHT22 temperature-humidity sensor, MQ-4 gas sensor, rain sensor, RC522 RFID module, and servo motors. The selected components offer a good balance between performance, cost, and availability (Minoli et al., 2017; Google, 2024).

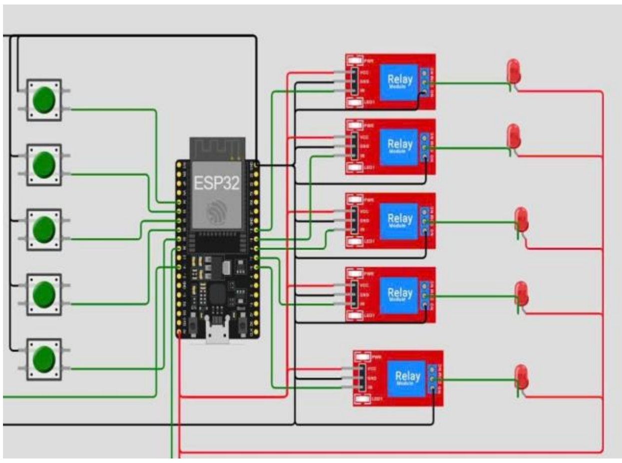

Figure 3. Lighting control circuit diagram

Source: Authors, 2025

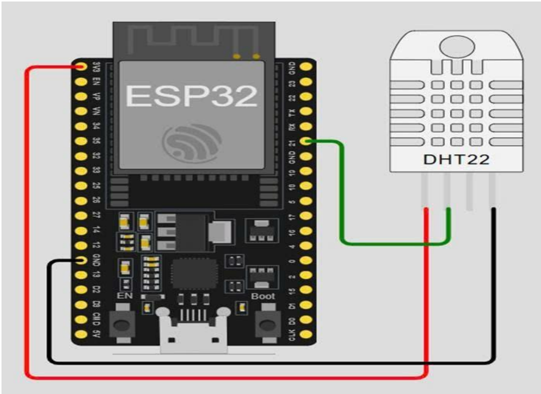

Figure 4. Temperature and humidity sensor circuit diagram

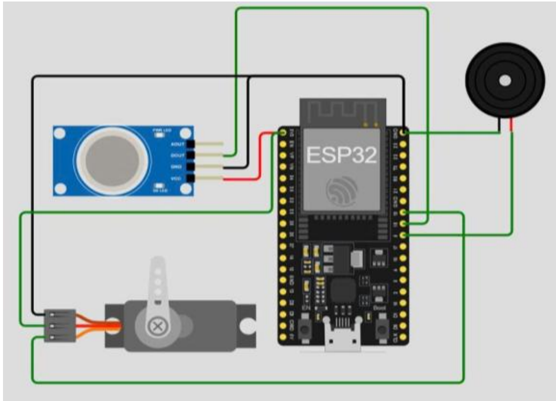

Figure 5. Gas leakage detection circuit diagram

Source: Authors, 2025

Detailed specifications of each component were presented and validated during experimental implementation.

3.4. Monitoring and control interface

The monitoring and control interface is developed on the E-Ra IoT Platform, enabling real-time visualization of sensor data and remote device control (E-Ra Platform, 2024). Environmental trends are displayed using temperature and humidity charts, providing useful insights for future intelligent automation development.

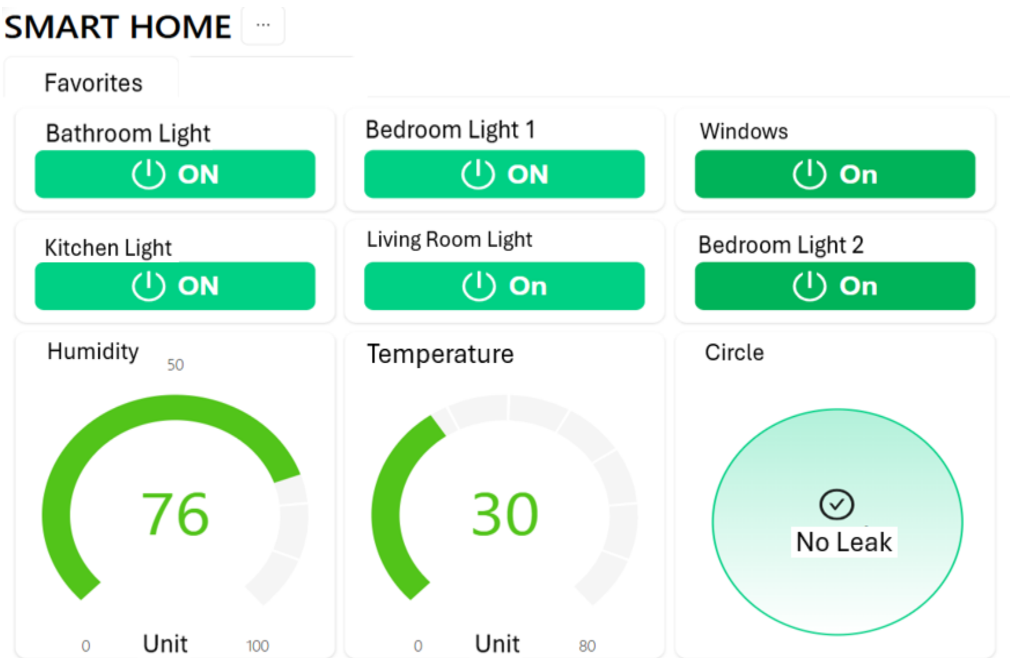

Figure 6. Smart home monitoring and control dashboard interface

Source: Authors, 2025

The dashboard displays lighting status, temperature and humidity values, and safety sensor states.

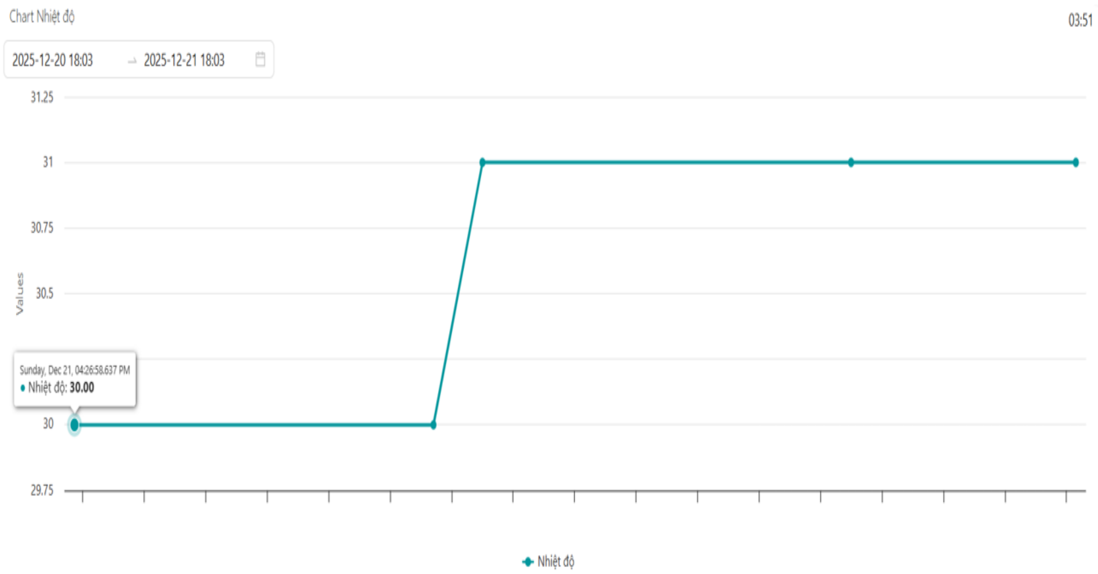

Figure 7. Temperature variation over time recorded by the system

Source: Authors, 2025

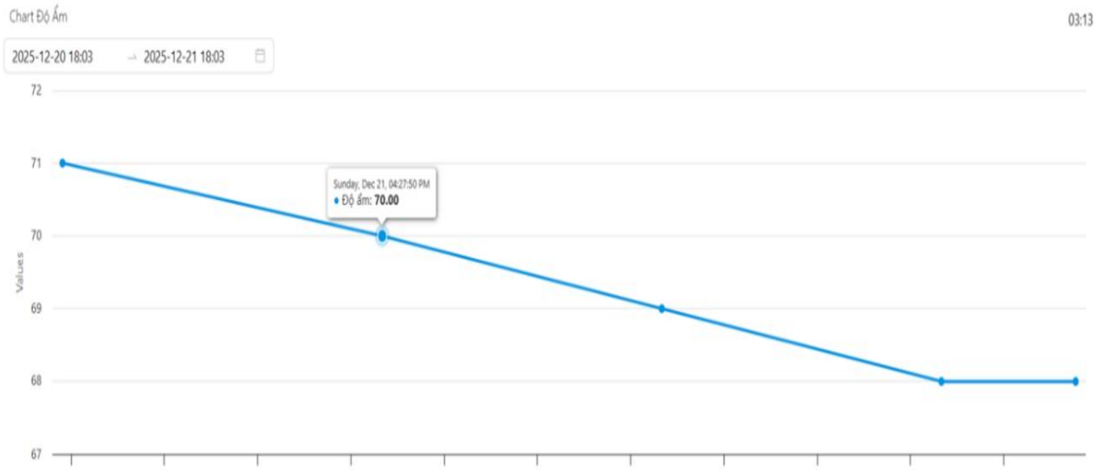

Figure 8. Humidity variation over time recorded by the system

Source: Authors, 2025

4. Experimental Results and Discussion

4.1. Experimental results

The proposed smart home model was fully assembled and tested under real operating conditions using a physical prototype.

Figure 9. Physical prototype of the proposed smart home model

Source: Authors, 2025

Figure 9 illustrates the physical prototype used in the experiments, integrating lighting control, access control, environmental sensing, and automation components within a compact smart home layout. The embedded sensors, actuators, and control units were used to validate voice control, environment-driven automation, and centralized monitoring under real operating conditions.

Experimental results indicate that all core functions operate as intended, including remote lighting control via the dashboard, door access using RFID and keypad passwords, gas leakage detection and alerting, automatic drying rack control during rainfall, and voice-based device control via Google Assistant (Google, 2024).

The system prototype was tested continuously for approximately 48 hours under normal operating conditions. During this period, different control commands and sensor-triggered events were repeatedly performed in order to observe the stability and responsiveness of the system. Each main functions, including remote lighting control, RFID/keypad door access, gas leakage detection, automatic drying rack operation, and voice control-was executed at least 20 times.

Throughout the testing period, the system operated stably and no functional failures were recorded. The response time for control commands was observed to be around one second in most cases, which is acceptable for typical smart home applications. However, extensive stress testing and long-term reliability evaluation were beyond the scope of this study and are left for future work.

Regarding response time, the system achieves an average response time of less than 1 second for basic control operations such as switching lights, opening doors, and activating actuators. For Internet-dependent functions such as voice control and remote IoT-based control, latency slightly increases but remains acceptable for residential applications.

Table 2. Summary of system functions and experimental results

Index	Function	Experimental results	Remarks
1	Remote lighting control	Stable operation	Fast response
2	RFID/keypad door access	Accurate	No false access
3	Gas leakage detection	Timely detection	Alarm activated
4	Rain-based drying rack	Accurate automation	High reliability
5	Voice control	Correct command execution	Internet dependent

Source: Authors, 2025

4.2. Discussion

In terms of response time, the experimental results indicate that the proposed system achieves an average response time of less than 1 second for basic control operations. This performance is comparable to typical IoT-based smart home systems reported in previous studies (Zanella et al., 2014; Al-Kuwari et al., 2021).

It should be noted that the response latency of IoT-based smart home systems may vary depending on several factors, including network conditions, communication protocols, and hardware configuration. For example, systems based on microcontrollers such as ESP8266 can also achieve response times below 1 second when properly optimized.

Therefore, the primary advantage of the proposed system lies not necessarily in achieving lower latency, but in providing a stable and integrated architecture that combines voice control, environment-based automation, and centralized monitoring within a low-cost smart home platform.

Compared with traditional manual control methods, the proposed model offers significant advantages in convenience and safety. Environment-based automation functions, particularly gas leakage detection and automatic drying rack control, reduce user dependency and mitigate risks in emergency situations (Piyare, 2013).

When compared with commercial smart home solutions, the proposed system does not aim to compete in terms of advanced artificial intelligence integration but focuses on low cost, flexibility, and ease of deployment. Although it does not yet achieve the advanced security and automation levels of commercial ecosystems, it sufficiently meets the basic requirements of residential housing and offers strong potential for future expansion (Zanella et al., 2014; Gupta & Johari, 2020).

Nevertheless, some limitations remain. The system relies on Internet connectivity for remote and voice-based control, which may reduce performance under unstable network conditions. Additionally, data security mechanisms are currently basic and do not yet incorporate advanced encryption and authentication techniques, which should be addressed in future work.

Overall, the results demonstrate that the proposed smart home model achieves a balanced trade-off between performance, cost, and deployability, making it suitable for research, education, and experimental real-world applications.

5. Conclusion and future work

This paper has presented the design, implementation, and evaluation of a smart home model integrating voice control and environment-based automation based on the Internet of Things. By combining ESP32 and Arduino Mega 2560 microcontrollers, the system successfully integrates smart lighting control, temperature–humidity monitoring, gas leakage detection and mitigation, RFID- and password-based door access, automatic drying rack control, and voice control via Google Assistant.

Experimental results obtained from a physical prototype confirm that the system operates stably, achieves fast response times (less than 1 second for basic operations), provides real-time monitoring, and offers an intuitive user interface. The use of the E-Ra IoT Platform simplifies deployment and allows future system expansion without major hardware modifications.

Although the proposed model meets its initial objectives, further improvements are possible. Future research directions include enhancing system security and data protection, expanding intelligent data-driven automation, integrating advanced security features, supporting multi-platform interaction, and deploying the system in real residential environments to evaluate long-term stability, scalability, operational costs, and energy-saving efficiency. These developments will provide a foundation for deeper research and potential commercialization.

References

Al-Kuwari, M., Ramadan, A., Ismael, Y., Al-Sughair, L., Gastli, A., & Benammar, M. (2021). Smart-home automation using IoT-based sensing and monitoring platform. *IEEE Access, 9*, 77529–77541. https://doi.org/10.1109/ACCESS.2021.3083602

Alam, M. R., Reaz, M. B. I., & Ali, M. A. M. (2012). A review of smart homes—Past, present, and future. *IEEE Transactions on Systems, Man, and Cybernetics: Part C (Applications and Reviews), 42*(6), 1190–1203. https://doi.org/10.1109/TSMCC.2012.218920

Arduino. (2023). *Arduino Mega 2560 Rev3 – Technical specifications*. Arduino S.r.l. https://www.arduino.cc

Atzori, L., Iera, A., & Morabito, G. (2010). The Internet of Things: A survey. *Computer Networks, 54*(15), 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010

E-Ra Platform. (2024). *E-Ra IoT platform documentation*. https://e-ra.io

Espressif Systems. (2023). *ESP32 series datasheet*. Espressif Inc. https://www.espressif.com

Esposito, M., et al. (2023). Design and implementation of a framework for smart home automation based on cellular IoT, MQTT, and serverless functions. *Sensors, 23*(9), 4459. https://doi.org/10.3390/s23094459

Google. (2024). *Google Assistant documentation*. Google LLC. https://developers.google.com/assistant

Gupta, A., & Johari, R. (2020). IoT-based smart home using ESP32. In *Proceedings of the International Conference on Smart Systems and Inventive Technology (ICSSIT)* (pp. 104–109). IEEE. https://doi.org/10.1109/ICSSIT48917.2020.9214177

Iliev, Y., et al. (2022). A framework for smart home system with voice control using NLP methods. *Electronics*, *12*(1), 116. https://doi.org/10.3390/electronics12010116

Irugalbandara, C., et al. (2023). A secure and smart home automation system with speech recognition and power measurement capabilities. *Sensors*, *23*(13), 5784. https://doi.org/10.3390/s23135784

Kumar, S., & Singh, R. P. (2017). Internet of Things: A survey on enabling technologies, protocols, and applications. *Journal of Network and Computer Applications*, *79*, 1–20. https://doi.org/10.1016/j.jnca.2016.11.023

Li, S., Xu, L. D., & Zhao, S. (2015). The Internet of Things: A survey. *Information Systems Frontiers*, *17*(2), 243–259. https://doi.org/10.1007/s10796-014-9492-7

Minoli, D., Sohraby, K., & Occhiogrosso, B. (2017). IoT considerations, requirements, and architectures for smart buildings: Energy optimization and next-generation building management systems. *IEEE Internet of Things Journal*, *4*(1), 269–283. https://doi.org/10.1109/JIOT.2016.2647881

Piyare, R. (2013). Internet of Things: Ubiquitous home control and monitoring system using Android-based smart phone. *International Journal of Internet of Things*, *2*(1), 5–11.

Nguyen, H. S., Nguyen, D. N., Pham, T. A., Nguyen, D. T., & Bui, D. M. (2020). ECHONET Lite-based IoT platform for smart homes. In *Proceedings of the 2020 RIVF International Conference on Computing and Communication Technologies (RIVF)*. IEEE.

Nguyen, T. T., & Nguyen, D. N. (2019). Design and implementation of an IoT-based smart home system using ESP8266. *International Journal of Engineering and Technology*, *8*(2), 105–109.

Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for smart cities. *IEEE Internet of Things Journal*, *1*(1), 22–32. https://doi.org/10.1109/JIOT.2014.2306328