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IoT-Based Home Automation: A Modular System with Smart Monitoring and Control Features

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ABSTRACT

This study designed and developed a smart, modular home automation system to improve household energy efficiency and convenience through automated control, real-time monitoring, and remote access. The Incremental Prototyping Model was employed, allowing the system to be built in distinct, independently developed components. Core technologies included single-board computers and microcontrollers, specifically Raspberry Pi and NodeMCU, which provided versatility, computational power, and efficiency. The system also integrated sensors, actuators, and communication modules for environmental monitoring, security, and energy management, resulting in a robust and user-friendly solution. System effectiveness was evaluated using ISO 25010 standards. Results revealed an outstanding overall rating of 4.70, indicating a unanimous "Strongly Agree" from participants. This rating highlights excellent performance across functional suitability, performance efficiency, compatibility, usability, reliability, security, maintainability, and portability. The findings demonstrate that the system can seamlessly manage diverse home-related functions, offering a tailored and adaptable solution for modern households.

Index Terms: Home Automation, Raspberry-Pi, NodeMCU, IoT, ISO25010

INTRODUCTION

The trend of smart homes is rapidly expanding with the advancement of technology and the Internet of Things (IoT). An intelligent home automation system provides an easy and convenient way to control and monitor various devices and appliances within the household [1]. At its core, IoT consists of sensors that collect data and connect to the internet either wirelessly or through wired networks. The data is then captured, stored, and analyzed digitally, minimizing the need for human intervention. The resulting insights can be utilized by machines and, when necessary, by humans to refine and optimize monitored activities [2][3].

According to the World Economic Forum's State of the Connected World 2020 report, IoT is playing a vital role in enabling smart homes, which are becoming increasingly popular as more people adopt digital technologies to automate and control their home environments. The report highlights that the global IoT market is projected to grow at a compound annual growth rate (CAGR) of 26.9% between 2020 and 2025, driven by the widespread adoption of smart home devices and other IoT applications [4]. It also emphasizes key trends and challenges, including the growing need for interoperability and standardization to enable seamless integration of devices and platforms, as well as the critical importance of ensuring data privacy and security in smart homes.

However, most existing smart home automation systems remain limited in functionality and scalability, making it difficult for users to customize and upgrade their systems to meet evolving needs [5][6]. Current solutions often lack scalability, ease of use, and integration capabilities necessary to fully realize the

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potential of intelligent home technology [7]. Many systems are complex to install, difficult to operate, and unable to effectively accommodate the growing number of devices in modern homes, resulting in fragmented user experiences and limiting the benefits of home automation [8].

This research seeks to address these limitations by designing and developing a modular smart home automation system using Raspberry Pi and NodeMCU microcontrollers. The proposed system is user-friendly, easily integrates with multiple devices and platforms, and supports future expansion as the number of connected devices increases. It features a simple and intuitive interface, efficient device integration, and a scalable architecture to provide a seamless and convenient home automation experience. The goal is to create a solution that maximizes the benefits of home automation technology and improves homeowners' quality of life. In the system design, the Raspberry Pi functions as the central hub, managing the user interface for monitoring and controlling devices, while the ESP32 handles direct device and appliance operations, leveraging its low power consumption and strong connectivity features.

RELATED STUDIES

To underscore the importance of interoperability in IoT systems, Abdelouahid et al. proposed an innovative approach to building an interoperable IoT platform using open-source software. Their solution, developed on the Open HAB framework, allows seamless integration of devices from different manufacturers, operating systems, and communication technologies, creating a "network of everything." The platform is flexible, scalable, and applicable across diverse domains, including automotive, consumer electronics, commerce, healthcare, home automation, and industry. It features a web application and virtual assistants to enable device-to-device and device-to-service interactions. For instance, a motion detector can trigger smart lighting or adjust climate controls in real time. The authors validated their approach through the development of a universal intelligent object prototype, demonstrating high interoperability across devices and proving its effectiveness in case studies such as smart building applications [8].

Similarly, Setz et al. conducted a comprehensive technical review of 20 open-source home automation systems to identify architectural commonalities. Their analysis was carried out in two phases. In the first phase, the authors extracted key features and performed a use case-based evaluation focusing on lighting control, temperature control, and security monitoring. In the second phase, they applied a criteria-based analysis using 34 criteria covering aspects such as setup time, documentation quality, pricing, and hardware requirements. From this process, the four most promising platforms—OpenHAB, Home Assistant, Domoticz, and FHEM—were identified and compared in detail. This review provides valuable insights into the strengths and limitations of leading open-source smart home automation solutions [9].

METHODOLOGY

Methodology

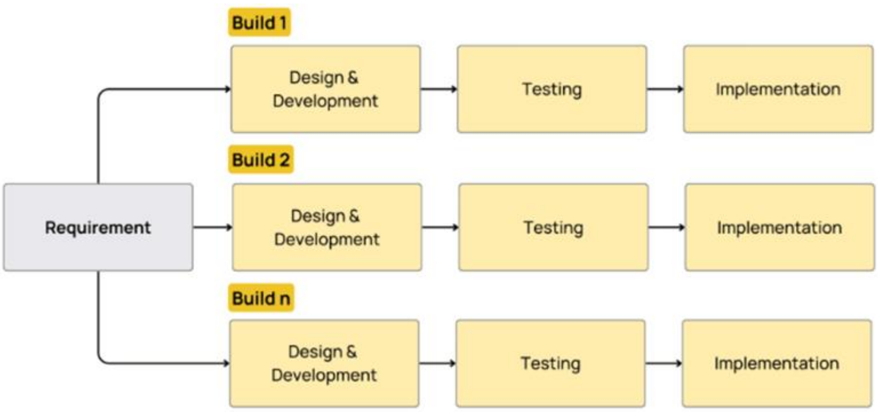

Figure 1. Incremental Prototyping Model

Figure 1 illustrates the Incremental Prototyping Model, showing the cyclical process of prototype development, evaluation, refinement, and integration until the complete system is achieved.

This study adopts the Incremental Prototyping Model as its software development methodology. This model was chosen because it allows the system to be developed in manageable parts or "prototypes," which can be built, evaluated, and improved in stages until the final system is completed. Unlike the traditional linear approach, the Incremental Prototyping Model emphasizes flexibility and continuous refinement, making it suitable for projects that require user feedback and iterative improvements.

In this approach, the researchers divided the proposed smart home automation system into several functional components, such as environmental monitoring, smart security, energy management, and user interface control. Each component was developed as a prototype and then integrated into the system incrementally. This process ensured that feedback could be gathered at every stage of development, allowing the researchers to make necessary adjustments before progressing to the next prototype.

Architecture

The architecture of the proposed IoT-Based Home Automation System is structured to seamlessly integrate devices, gateways, and internet services into a unified environment for monitoring, control, and data management. As illustrated in Figure 2, the system is composed of three major layers: the Device Layer, the IoT Gateway Layer, and the Internet Layer, each performing distinct yet interconnected functions.

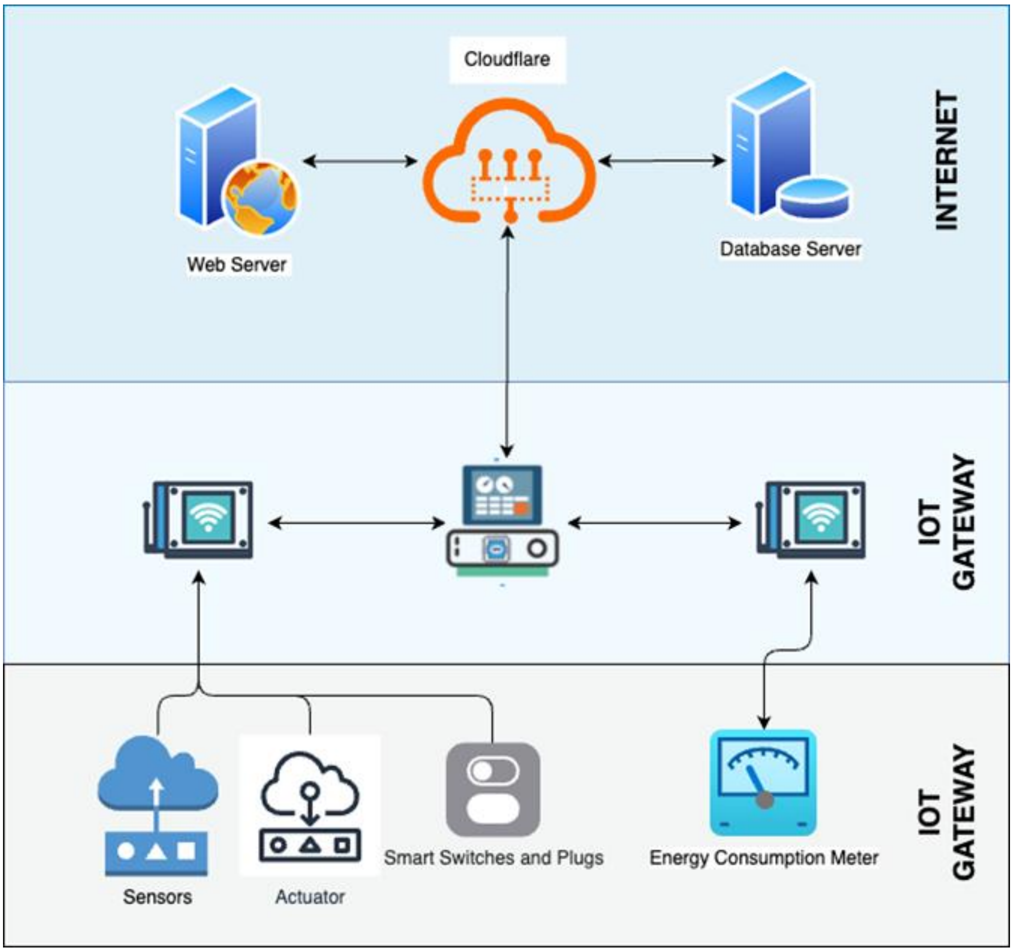

Figure 2. System Architecture of the Proposed IoT-Based Home Automation

The system architecture is structured into three layers. At the Device Layer, physical smart devices such as sensors, actuators, smart switches, plugs, and energy meters form the foundation by collecting environmental data and executing automation commands. These devices communicate with the IoT Gateway Layer, where

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microcontrollers like the Raspberry Pi and ESP32 process and transmit data, ensuring scalability by allowing new devices to be added without disrupting existing functions.

At the Internet Layer, communication, storage, and user interaction are managed through a web server and database server, providing real-time monitoring, control, and secure storage of data. Cloudflare is integrated to protect against cyber threats and enable encrypted transmission. Overall, this workflow ensures efficient data collection, processing, storage, and user control, resulting in a scalable, secure, and user-friendly home automation solution that addresses energy management, environmental monitoring, and household security.

RESULT AND DISCUSSION

The Developed System

Figure 3. Some of the Modules Included in the Project

This study developed an IoT-Based Home Automation System designed to enhance household convenience, security, and energy efficiency through intelligent monitoring and control. The system integrates key hardware components, including the Raspberry Pi 3B+, NodeMCU, and ESP32 microcontrollers, along with various sensors and actuators. Supported by Home Assistant, ESPHome, and Cloudflare technologies, the system enables real-time monitoring, secure remote access, and seamless integration of multiple devices, forming a robust and interconnected smart home environment.

Several functional modules were designed and implemented as part of the system. The temperature and humidity module, built with the AHT20 sensor, ESP32 microcontroller, and OLED display, provides accurate and real-time environmental monitoring in a compact and user-friendly form. The smart outlets and switches, developed using ESP32 microcontrollers and relay modules, allow users to remotely control appliances and lighting fixtures, supporting both convenience and energy conservation. The gas leak detector, equipped with an MQ2 sensor and ESP32, offers reliable detection of combustible gases such as methane, propane, LPG, and smoke, triggering safety alerts to prevent potential hazards. Similarly, the motion detector, which integrates a PIR sensor with the ESP32, enhances home security by detecting movement and initiating automated actions, such as activating lights or sending real-time notifications.

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To address household security, the system also includes a smart door lock that combines an MRC522 RFID scanner with an ESP32 microcontroller. This module provides secure access control by verifying RFID cards or tags against a predefined database, granting, or denying entry accordingly. Finally, the smart energy meter, developed using the PZEM-004T V3 module and ESP32, accurately measures electrical parameters such as voltage, current, power, and energy consumption, providing users with real-time insights into their energy usage patterns.

Collectively, these modules highlight a modular, scalable, and user-friendly smart home automation system. By integrating sensing, control, and monitoring functions into a unified platform, the project demonstrates how IoT technologies can be harnessed to create efficient, secure, and adaptable solutions for modern households.

System Evaluations Test Result

The developed IoT-Based Home Automation System was evaluated based on the ISO/IEC 25010 software quality model, covering eight quality characteristics: Functional Suitability, Performance Efficiency, Compatibility, Usability, Reliability, Security, Maintainability, and Portability. 13 respondents participated in the evaluation, composed of eight (8) IT practitioners, two (2) graduates of Doctor in Information Technology (DIT), and three (3) faculty members handling IT professional courses. Their diverse backgrounds ensured that the assessment was comprehensive, balancing perspectives from industry experts, academic scholars, and professional educators.

TABLE II User Evaluation Test Results

Factors	**Weighted Mean**	**Verbal Interpretation**	**Rank**
Functional Suitability	4.70	Strongly Agree	5
Performance Efficiency	4.75	Strongly Agree	2
Compatibility	4.73	Strongly Agree	3
Usability	4.72	Strongly Agree	4
Reliability	4.58	Strongly Agree	8
Security	4.83	Strongly Agree	1
Maintainability	4.63	Strongly Agree	7
Portability	4.67	Strongly Agree	6
Overall Weighted Mean	**4.70**	**Strongly Agree**	

Table II shows that the system achieved an overall weighted mean of 4.70 (Strongly Agree), demonstrating that it effectively met user expectations across key quality factors. Evaluators confirmed that the system’s core functions—monitoring, control, and automation—are dependable and aligned with smart home requirements.

Efficiency and compatibility received high ratings, credited to the system’s lightweight protocols, optimized ESPHome firmware, and seamless integration with various devices. The user interface was also praised for its accessibility, allowing even non-technical users to navigate the Home Assistant dashboard easily.

While reliability scored slightly lower due to connectivity and internet dependency, evaluators suggested enhancing offline capabilities for greater robustness. Security emerged as the highest-rated factor, with Cloudflare tunneling and RFID-based access providing strong safeguards. Maintainability and portability were rated positively, though improvements in simplifying updates and troubleshooting were recommended.

Overall, the results confirm that the system is secure, efficient, user-friendly, and adaptable. Feedback from IT practitioners, DIT graduates, and faculty members validated both the practical utility and academic rigor of the developed solution.

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CONCLUSIONS

Based on the evaluation results, the developed IoT-Based Home Automation System successfully met the objectives of the study by providing a secure, efficient, and user-friendly solution for smart home management. The system obtained an overall weighted mean of 4.70, interpreted as "Strongly Agree," indicating that the evaluators, composed of eight IT practitioners, two graduates of Doctor in Information Technology, and three IT faculty members, found the system highly effective across all quality dimensions of the ISO/IEC 25010 software quality model.

Overall, the findings affirm that the system provides functional suitability, high performance efficiency, compatibility with multiple devices, strong usability, and secure access while maintaining portability and adaptability in various home environments. With further refinements in reliability and maintainability, the system can be positioned as a practical and scalable home automation solution for broader adoption.

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