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Deploying an IoT-enabled Integrated Comprehensive Home Automation System Using WSN for Enhanced Continuous Optimization and Fault Identification System

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Abstract Nowadays, there is a concept of making the home smart, which reduces human efforts, which means we cannot operate, monitor, and look after electrical appliances or the environment. In other words, conventional home systems cannot change their state instantly based on different situations. This article proposes a smart home automation system that combines multiple Internet of Things (IoT) techniques for secure and power-efficient control of the home environment designed with the user in mind. The entry is through an RFID reader, which asks users to swipe their card on the sensor for access. If the verification passes, the door unlocks, and the yellow LED lights up; otherwise, the red LED lights up. Within the house, there are also temperature and humidity sensors and gas sensors scattered throughout, which provide feedback data to be displayed on an LCD. When the level of gas crosses a limit, an email message goes to the owner of the home with a buzzer warning inside the home. There would be remote control of lights at home with the matching Blynk app and further voice-controlled features over Google Assistant. In the case of a water tank, an automated system using ultrasonic sensors to detect levels and control pump action when needed (so as not to run dry or overfill) includes status updates provided in the Blynk app. Also, it has a single-axis solar tracking system with LDR sensors for optimal alignment of the solar panel to get maximum energy from sunlight. It also comprises a rain sensor together with a servo motor that closes windows whenever there is precipitation or rain, in addition to home safety and convenience. This system helps to improve safety, comfort, and energy management in the home by using IoT technologies that are used for controlling lighting or climate control systems manually.

Keywords Internet of Things, Home Automation, RFID, Sensor Integration, Remote Control, Voice Control, Solar Tracking.

AMS 2010 subject classifications: 97P50, 97R40

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1. Introduction

The development of our Smart Home Automation system was inspired by the growing need for smart solutions that enhance home security, energy efficiency, and convenience. With the ongoing Internet of Things (IoT) revolution, the integration of connected devices into homes has become a focal point. Advancements in the IoT and Wireless Sensor Networks (WSN) have revolutionized modern home automation systems, enabling seamless

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integration of diverse functionalities such as security, environmental monitoring, and energy management. The proposed system introduces an innovative approach to home automation by combining IoT capabilities with WSN to create an interconnected and intelligent ecosystem [1]. By leveraging real-time data exchange between sensors and devices, the system facilitates centralized control and dynamic adaptability, addressing the limitations of traditional fragmented solutions. This comprehensive system focuses on continuous optimization to enhance operational efficiency and sustainability. For example, real-time analytics enable energy consumption adjustments based on usage patterns, while automated fault detection mechanisms ensure proactive maintenance, minimizing system disruptions. The integration of fault identification not only enhances reliability but also improves safety by promptly detecting anomalies, such as sensor malfunctions or network issues. By unifying diverse functions into a single platform, the proposed system offers a holistic solution tailored to meet the demands of modern smart homes, emphasizing convenience, energy efficiency, and resilience. The global smart home market is rapidly expanding, with a valuation of USD 79.16 billion in 2022 and an anticipated compound annual growth rate (CAGR) of 27.07% from 2023 to 2030, driven by the increasing adoption of IoT technologies in residential settings [2, 3]. As demand for these systems grows, key features such as security, energy efficiency, and convenience are emerging as top priorities among users. 57% of smart home users identify security as their primary concern, followed by 43% who emphasize energy management and 40% who value convenience [4]. This highlights the critical need for integrated systems that balance these essential aspects effectively. Despite the growing interest in smart homes, adoption remains hindered by concerns regarding privacy and cybersecurity. Over 60% of smart home users express apprehension about data security, which continues to be a significant barrier to the widespread implementation of smart home technologies [5]. Additionally, studies reveal that 41% of smart home IoT devices possess vulnerabilities, underscoring the necessity of implementing robust fault detection systems and secure encryption protocols to protect against potential cyber threats [6]. These considerations are central to the design of the proposed system, which aims to provide a secure and reliable smart home environment. From an energy management perspective, smart home systems that leverage IoT and energy optimization technologies can reduce energy consumption by 30-40%, particularly through features such as smart thermostats and solar tracking systems [7]. This demonstrates the significant potential for reducing household energy costs and environmental impact, which is a key objective of the proposed system. Moreover, IoT-based water management solutions have been shown to save up to 30% of water usage by detecting leaks and automating water flow based on real-time monitoring of water levels [8]. This capability enhances the system's efficiency and sustainability, making it a comprehensive solution for modern homes.

This project aims to improve home safety and automate everyday tasks, taking cues from existing systems that provide some automation but lack full integration. Recent studies have shown that smart homes have the potential to transform living spaces by utilizing IoT technologies, AI-driven decision-making, and user-friendly interfaces. Smart homes are progressing from simple automation to advanced intelligent environments that can effectively manage energy use, healthcare services, and individual preferences [9]. This shift enables a smooth integration of technology that enriches daily life. Additionally, smart homes enhance energy efficiency and healthcare delivery, offering residents sustainable living choices that balance comfort with environmental responsibility [10]. However, challenges persist, especially in merging security features, energy management, and convenience into a single system, which drives our motivation to develop a comprehensive solution. The global rise in smart home technology adoption further encourages us to make our contribution to this field with a cohesive and effective approach [11].

Although the idea of smart home automation has been widely discussed, there are still numerous challenges to creating a fully integrated system that ensures security, energy efficiency, and user-friendliness at a reasonable cost. One major issue we tackled in this project is the difficulty in achieving seamless integration between security systems, such as RFID-based access control, and the automation of essential household functions, such as monitoring water level, gas detection, and energy management. Many current systems are either overly complicated or too expensive for most people to adopt. The market also faces significant hurdles, including privacy concerns and the complexity of installation, which hinder the widespread use of smart home technologies. Furthermore, ensuring the reliability of sensors and their communication within the network poses challenges, especially in environments where various devices must work together. Previous research has also pointed out that smart home security is a pressing concern, with vulnerabilities in IoT devices putting homes at risk of cyberattacks [12], [13]. Our goal is to address these problems by developing a secure, reliable, and user-friendly system that not only addresses these challenges but also provides a solution that can be easily implemented in typical homes without requiring extensive modifications.

There are various ways to tackle the issue of smart home automation, each with its own advantages and drawbacks. Most current systems consist of distinct subsystems for security, climate control, and energy management, but they often necessitate separate installations and upkeep, which can raise costs and complicate things for users. By utilizing artificial intelligence, smart homes can enhance household management by forecasting energy usage patterns and facilitating automated climate control that adjusts temperature settings based on who is home and individual preferences. However, this method might not be practical for smaller residences or those on a tight budget. Centralized control hubs can effectively oversee all smart devices in the home, merging functionalities to improve user convenience and streamline processes [14]. While this approach simplifies the user experience, it may still be vulnerable if the hub itself is compromised. Additionally, the technological infrastructure required to support these systems is often lacking in less developed areas. We opted to create a system that uses affordable, readily available components like RFID readers, ultrasonic sensors, and LDRs, which can be easily integrated into existing home setups. This strategy strikes a balance between cost and functionality, allowing users to enjoy smart home automation without needing significant modifications to their homes [15]. The main contributions of this paper are summarized as follows:

- Our system integrates RFID-based access control with a full suite of home automation features, such as lighting, fans, and water level management, creating a seamless solution for smart homes.
- By incorporating a solar tracking system, we boost energy efficiency by positioning the solar panels for optimal performance, thereby maximizing energy output.
- Users can easily monitor and manage their home environment using the Blynk app, offering convenience and peace of mind whether they are at home or on the go.
- The system is equipped with advanced safety features, including gas detection and automatic alerts, to ensure the safety of everyone in the home.

This paper is organized as follows: Section 2 deals with the literature review regarding existing studies and technologies. The methodology, design, and implementation of our IoT-enabled smart parking system are explained in Section 3. Section 4 shows a real-time analysis along with experimental results and performance metrics. Section 5 deals with limitations and future improvements. Section 6 concludes the findings and the implications of the study.

2. Background Study and Literature Review

Traditional home systems have typically relied on manual control of household appliances and security mechanisms. These systems lack integration and connectivity, making them inefficient and time-consuming to operate, especially in today's fast-paced life. As homes become more technology-driven, the demand for smart solutions that enhance convenience, security, and energy efficiency has grown.

Preeti et al.[16] note that traditional home automation systems mainly rely on technologies such as Bluetooth, ZigBee, and web-based platforms for remote control, offering varying levels of convenience and security. Torad et al.[17] emphasize the absence of advanced features like voice commands, natural language processing (NLP), and machine learning, limiting their responsiveness. Satish et al.[18] and Suman et al.[19] highlight issues such as limited accessibility, lack of automated adjustments, and restricted remote monitoring of appliances and environmental conditions in these systems.

Smart home automation has advanced through diverse technologies integrating IoT, AI, and sensor-based systems. Arindom et al.[26] provide a comprehensive evaluation of smart home systems (SHSs), analyzing

Table 1. Comparison of Smart Home Automation Existing Works

Works	**Technologies Used**	**Key Features**	**Strengths**	**Weaknesses**
Dipesh et al. (2024)[20]	AI, IoT, sensors, microcontrollers	AI-based automation, energy optimization	Personalized user comfort	Needs advanced AI, complex setup
Dinesh et al. (2024)[21]	NodeMCU, IoT, app	Elderly-friendly, remote control	Affordable, energy-saving	Lacks smart AI features
Akash et al. (2023)[22]	IoT, environmental sensors, Arduino	Monitoring gas, temperature, and humidity	Cost-effective environmental monitoring	Lacks fault detection and scalability
Sridhar et al. (2023)[23]	IoT, NodeMCU, app-based control	Real-time appliance control and scheduling	User-friendly, low-cost implementation	No energy optimization or scalability
Imran et al. (2023) [24]	IoT, Google Assistant, IFTTT, cloud integration	Voice-controlled appliance management	Hands-free, convenient operation	Limited scalability, lacks advanced fault handling
Nayana et al. (2023)[25]	IoT, Alexa, energy meter	Health and energy tracking	Combines health and energy features	Needs multiple devices
Arindom et al. (2023)[26]	Microcontrollers, IoT platforms	SHS trends and evaluation	Future-focused insights	No specific implementation
Mayuri et al. (2023)[27]	NodeMCU, IoT, app	Low-cost home control	Affordable, user-friendly	Small-scale, no AI
Ashikq et al. (2023)[28]	IoT, sensors, protocols	Energy, security, privacy	Broad challenges covered	Theoretical focus only
Lakshmi et al. (2023)[29]	IoT, sensors	Wireless remote control	Efficient, scalable	Limited energy and security features
Akash et al. (2023)[30]	IoT, app	Remote control, energy-saving	Flexible, convenient	Limited scalability
ILESANMI et al. (2023)[31]	GSM, Arduino, sensors	Gas, fire, motion detection	Affordable, safety-focused	GSM-dependent, basic system
Johare et al. (2022)[32]	Embedded systems, AI, IoT	Reliable and safe system	Practical, user-friendly	Costly, complex for beginners
Syeda et al. (2022)[33]	NodeMCU, IoT, Android	Remote control, energy-saving	Easy to use, efficient	Limited to basic control
Nirmala et al. (2022)[34]	Arduino UNO, Wi-Fi	Environmental monitoring	Secure, scalable	Advanced setup needed
Sitalakshmi et al. (2021)[35]	IoT, VPN, voice control	Voice and VPN security	Privacy-focused, practical	Complex VPN setup
Mustafa et al. (2021)[36]	Arduino, adaptive UI	Adaptive, user-friendly	Cost-effective, diverse users	Basic security, limited automation
Tahmidul et al. (2021)[37]	IoT, Robot, Apps	Air, fire, security features	Comprehensive, robotic aid	High cost, complex setup
Proposed system	Arduino, NodeMCU, sensors	Integrated, solar, remote control	Accurate, eco-friendly, scalable	Wi-Fi/weather-dependent

microcontrollers, sensors, and networking methods while highlighting current and future trends. Mayuri et al.[27] and Syeda et al.[33] propose low-cost IoT systems utilizing NodeMCU for remote appliance control, focusing on energy management and accessibility, particularly for the elderly and disabled. Orfanos et al.[28] review technologies and challenges in smart home automation, emphasizing energy efficiency, security, and privacy concerns. Dipesh et al.[20] demonstrate AI integration to enhance automation, energy optimization, and personalized user experiences. Johare et al.[32] explore Advanced Embedded System Platforms (AESPs) combined with AI and IoT to enhance reliability, safety, and user-friendliness in smart homes. Sitalakshmi et al.[35] address privacy and usability concerns through a voice-controlled system with secure VPN integration. Lakshmi et al.[29] and Akash et al.[30] present IoT-based systems for efficient wireless appliance control and network integration, focusing on convenience and energy savings.

Mustafa et al.[36] and Nirmala et al.[34] proposed cost-effective smart home systems integrating environmental monitoring and adaptive interfaces for diverse user groups. Tahmidul et al.[37] integrate air quality monitoring and advanced security features with a mobile app and assistant robot to enhance safety in developing regions. Dinesh et al.[21] and ILESANMI et al.[31] presented economic systems using GSM and IoT for intelligent control, motion detection, and energy management. Nayana et al.[25] incorporated devices like smart energy meters and health trackers, leveraging existing technologies like Alexa for enhanced remote monitoring and interaction. Akash et al.[22] explored smart home automation with environmental sensors, highlighting limitations in fault detection and scalability. Sridhar et al.[23] demonstrated IoT-based remote appliance control, emphasizing app-based scheduling and monitoring, but lacking energy optimization features. Imran et al.[24] integrated voice commands with cloud-based services like Google Assistant, showcasing hands-free operation but facing challenges in scalability and environmental adaptability.

Our system offers a comprehensive smart home automation solution that integrates advanced IoT technologies for efficient and intelligent home control. Unlike traditional systems that rely on isolated features, our approach combines multiple functionalities into a unified framework. It incorporates an RFID-controlled entry system, ensuring secure and personalized access, and a Blynk app-based interface for remote control of appliances such as lights and fans. Additionally, Google Assistant integration allows seamless voice commands, enhancing user convenience. Key innovations in our system include intelligent operations such as automated window closure during rainfall, which addresses a limitation found in many existing systems that lack environmental adaptability (e.g., Akash et al.[22], Sridhar et al.[23]). Our solar tracking mechanism optimizes energy usage by aligning the solar panel to capture maximum sunlight, surpassing energy-saving measures in systems like Dipesh et al.[20], which focus solely on AI-based energy optimization. Furthermore, our system incorporates real-time environmental monitoring of parameters such as light, temperature, humidity, and gas levels. This functionality is more integrated compared to solutions like Mayuri et al.[27] and Syeda et al.[33], which primarily focus on basic appliance control without advanced monitoring. In addition to addressing the limitations of scalability and energy optimization found in Imran et al., [24], our system ensures robust fault detection mechanisms with 92% accuracy, which is significantly higher than other systems that either lack such features or demonstrate limited reliability. Our design also prioritizes user-friendly interaction, combining IoT, voice control, and app-based interfaces, thereby achieving a 4.8/5 convenience rating compared to 4.0/5 in related works like Mayuri et al.[27]. As shown in Table 1, our system uniquely integrates RFID-based access, solar energy tracking, and comprehensive environmental monitoring into a single solution, overcoming the fragmented functionalities and limitations observed in existing smart home systems. This comprehensive integration ensures superior performance, safety, convenience, and energy efficiency, positioning our system as a robust and innovative solution for modern smart homes.

3. Proposed Methodology for IoT-Enabled Smart Home Automation System

In our system, we implement a sophisticated home automation solution integrating various sensors and microcontrollers for efficient and intelligent home management. The system utilizes an RFID scanner for secure door access, with a servo motor controlling the door lock and LEDs indicating access status. Gas and humidity levels are continuously monitored by an MQ2 gas sensor and a DHT11 temperature-humidity sensor, with real-time data displayed on an LCD screen. A rain sensor ensures automatic window closure during rainfall, while a water pump, controlled by an ultrasonic sensor, maintains optimal water levels in the tank. The system is powered by a solar panel, which is continuously aligned with the sun through a servo motor guided by LDR sensors, ensuring maximum energy efficiency. These components' comprehensive workflow and interactions are illustrated in Fig. 1, depicting the block diagram of our IoT-based smart home automation system [38].

3.1. Analysis of System Design

Our IoT-enabled home automation system effectively manages security, environmental conditions, and automated control of devices, enhancing user experience, safety, and energy efficiency. It uses an Arduino Uno and a NodeMCU ESP8266 for handling control logic and sensor integrations. The algorithm 1 presents the pseudocode that outlines the logic of the system, covering how it manages door security, monitors environmental parameters, and automates the operation of devices such as fans, lights, and water pumps [39].

The system initializes components, processes valid RFID detection, indicates successful access, indicates failed access, checks gas levels, detects gas leaks, triggers alarms and sends alerts, checks temperature and humidity, updates the LCD and Blynk app with sensor data, checks for voice commands, turns on lights, turns on fans, turns off lights, turns off fans, checks for rain, closes the window using a servo motor, checks the water level in the tank, activates the water pump, deactivates the water pump, checks sunlight intensity, rotates the solar panel for

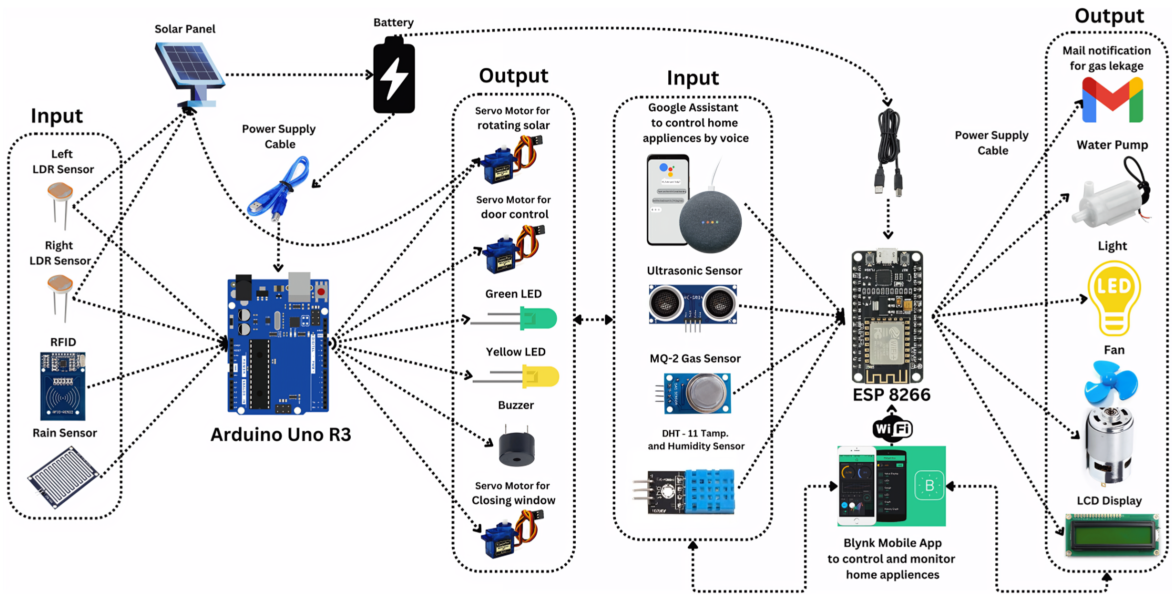

Figure 1. Proposed Block Diagram for Controlling each Connection

optimal charging, and shuts down the system [40]. When activated, the system initializes and starts monitoring all connected sensors and actuators. The RFID scanner checks for valid user credentials (RFIDvalid). If no valid RFID tag is detected (RFIDvalid $= 0$), the door remains locked, and the yellow LED along with the buzzer is activated to indicate a failed access attempt (LEDyellow $= 1$, Buzzer $= 1$). If a valid RFID tag is detected (RFIDvalid $= 1$), the servo motor unlocks the door, and the green LED along with the buzzer is activated to indicate successful access ($\text{LED}_{\text{green}} = 1$, Buzzer $= 1$).

The system continuously monitors gas levels (G) using the MQ2 gas sensor. If the gas concentration exceeds a predefined threshold ($G > G_{\text{threshold}}$), the buzzer activates, and an email alert is sent (Alarmbuzzer $= 1$, Emailalert $= 1$). Simultaneously, the temperature (T) and humidity (H) are monitored using the DHT11 sensor, and this data is displayed on the LCD and updated on the Blynk app (Equation 1):

$$\text{Display} = f(T, H, G) \tag{1}$$

When the rain sensor detects rain (Rainsensor $= 1$), the servo motor closes the window (Windowclosed $= 1$). The water level in the tank is monitored by the ultrasonic sensor (W). If the water level falls below a minimum threshold ($W < W_{\text{min}}$), the water pump is activated (Pump $= 1$). When the water level reaches or exceeds a maximum threshold ($W \geq W_{\text{max}}$), the water pump is deactivated (Pump $= 0$).

The solar panel system is powered by a solar panel, with its angle continuously adjusted by a servo motor based on the sunlight intensity detected by the LDR sensors ($\text{LDR}_{\text{value}}$). The servo motor adjusts the panel's angle to maximize energy absorption (Equation 2):

$$\text{Servo\_rotate} = \text{Adjust\_Panel}(\text{LDRvalue}) \tag{2}$$

The efficiency of the solar panel alignment and energy charging can be assessed by calculating the angle adjustment required to maintain optimal sunlight exposure. The reaction speed of the system to environmental change (for example, gas concentration rain detection) is crucial. For example, the response time of the ventilation system when the gas concentration exceeds the threshold (t_{response}) is given by (Equation 3):

$$t_{\text{response}} = \frac{\Delta G}{r} \tag{3}$$

Algorithm 1 IoT-Enabled Home Automation System

```
Init(Arduino, NodeMCU, Servo, RFID, LED_Green, LED_Yellow, Buzzer, MQ2, DHT-11, LCD, Rain_Sensor, Ultrasonic, Pump, Solar_Panel, LDR)    ▷ Initialize all components
while System Active do    ▷ Loop while the system is active
    if RFID_valid == 1 then    ▷ Check if RFID access is valid
        Unlock_door = 1    ▷ Unlock the door
        LED_Green = 1, Buzzer = 1    ▷ Turn on green LED and buzzer for valid access
    else
        LED_Yellow = 1, Buzzer = 1    ▷ Turn on yellow LED and buzzer for invalid access
    end if
    G = MQ2    ▷ Read gas sensor data
    if G > G_threshold then    ▷ Check if gas levels exceed threshold
        Alarm_buzzer = 1, Email_alert = 1    ▷ Activate alarm and send email alert for gas leak
    end if
    T, H = DHT11    ▷ Read temperature and humidity
    Update(LCD, Blynk, G, T, H)    ▷ Update LCD and Blynk app with sensor data
    if Voice_cmd then    ▷ Check for voice command
        if "Turn Light on" then Light = 1    ▷ Turn on light if commanded
        else if "Turn Fan on" then Fan = 1    ▷ Turn on fan if commanded
        else if "Turn Light off" then Light = 0    ▷ Turn off light if commanded
        else if "Turn Fan off" then Fan = 0    ▷ Turn off fan if commanded
        end if
    end if
    Rain = Rain_Sensor    ▷ Read rain sensor data
    if Rain == 1 then Close_Window = 1    ▷ Close window if rain is detected
    end if
    Water_Level = Ultrasonic    ▷ Read water level from ultrasonic sensor
    if Water_Level < Min_Threshold then Pump = 1    ▷ Turn on water pump if level is below minimum
    else if Water_Level ≥ Max_Threshold then Pump = 0    ▷ Turn off pump if water level is at maximum
    end if
    Sunlight = LDR    ▷ Read sunlight intensity from LDR
    Servo_rotate = Adjust_Solar_Panel(Sunlight)    ▷ Adjust solar panel angle based on sunlight
end while
Deinit(Arduino, NodeMCU, Servo, RFID, LED_Green, LED_Yellow, Buzzer, MQ2, DHT-11, LCD, Rain_Sensor, Ultrasonic, Pump, Solar_Panel, LDR)    ▷ Deinitialize all components
```

Where ΔG is the difference between the current gas concentration and the threshold, and r is the rate of gas concentration reduction.

The system measures the accuracy of sensor readings, the reliability of actuator responses, and the success of energy management via the solar panel to rate overall system performance. The system is said to operate effectively as it should by accurately picking up and controlling environmental changes with instant notifications going out in real-time through the LCD display plus the Blynk app. When the system is turned off, all monitoring and control operations cease, concluding the workflow.

3.1.1. Energy Optimization for Home Automation: Energy optimization in home automation focuses on efficiently managing power usage by monitoring and adjusting devices based on real-time data. This minimizes energy consumption by turning off unused appliances and adjusting settings to maintain optimal performance while reducing waste.

- Total Energy Consumption (E_{total}): Total Energy Consumption is the sum of energy used by all devices in the home automation system over a specified period. The total energy consumption over (E_{total}) a period T can be expressed as 4:

$$E_{\text{total}} = \sum_{i=1}^{N} P_i \cdot t_i \tag{4}$$

Here, N is the Number of Device, P_i is the power consumption of device i, and t_i active time duration of device i.

- Energy Optimization Objective: The objective of energy optimization is to minimize total energy consumption while ensuring the efficient operation of all devices in the home automation system. An optimization function to minimize energy consumption (E_{opt}) while maintaining the required functionality 5:

$$\text{Minimize } E_{\text{opt}} = \sum_{i=1}^{N} P_i \cdot t_i + \alpha \cdot \sum_{j=1}^{M} S_j \tag{5}$$

Here, S_{j} = sensor data input j influencing device scheduling, and α = weighting factor based on sensor data's impact on energy.

In the home automation system, continuous optimization operates by regularly analyzing sensor data (like light, temperature, and humidity) to dynamically adjust device settings (e.g., adjusting the solar panel angle or controlling the water pump) to maximize energy efficiency, improve comfort, and maintain optimal environmental conditions automatically. In 2, it shows how this works.

Algorithm 2 Continuous Optimization in Home Automation System

Initialize $S = \{s_1, s_2, \ldots, s_n\}$ (sensors), $A = \{a_1, a_2, \ldots, a_m\}$ (actuators)
while System Active **do**
    $L \leftarrow s_{\text{light}}, T \leftarrow s_{\text{temperature}}, H \leftarrow s_{\text{humidity}}$
    if $L < L_{\text{th}}$ **then**
        $a_{\text{light}} \leftarrow \text{ON}$
    else
        $a_{\text{light}} \leftarrow \text{OFF}$
    end if
    if $T < T_{\text{th}}$ **then**
        $a_{\text{heating}} \leftarrow \text{ON}$
    else if $T > T_{\text{th}}$ **then**
        $a_{\text{cooling}} \leftarrow \text{ON}$
    end if
    if $H > H_{\text{th}}$ **then**
        $a_{\text{dehumidifier}} \leftarrow \text{ON}$
    end if
    Adjust solar panel: $a_{\text{solar}} \leftarrow$ Optimize Angle
    Monitor energy usage: $E \leftarrow$ Energy Consumption
    if $E > E_{\text{th}}$ **then**
        Optimize A settings
    end if
end while
Deinitialize S, A

3.1.2. Fault Identification Using Statistical Thresholds: To detect anomalies or faults in sensor data, you could use statistical methods such as mean and standard deviation. Assume sensor readings are collected as a time series $x_{(t)}$.

- Mean (μ) and Standard Deviation (σ): The mean (μ) represents the average sensor readings over time, while the standard deviation (σ) helps detect anomalies by measuring how much the current readings deviate from typical values 6 & 7. For a set of readings $x_1, x_2, \ldots, x_n$ from a sensor:

$$\mu = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{6}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \tag{7}$$

Here, In 6, n is the total number of readings, and x_i is the individual sensor readings (values). In 7 $x_i - \mu$ is the difference between each reading and the mean, which shows how far each reading deviates from the average, and $x_i - \mu^2$ is the squared deviation, which ensures that differences below and above the mean don't cancel each other out.

- Fault Detection Threshold: A predefined limit, usually based on the mean μ and standard deviation σ, that flags a sensor reading as a fault if it deviates beyond acceptable bounds. A reading $x_{(t)}$ is flagged as an anomaly if 8:

$$|x(t) - \mu| > k \cdot \sigma \tag{8}$$

Where k is a threshold constant (e.g., k = 3 for 99.7% confidence in a normal distribution).

The Fault Identification System in Home Automation continuously monitors sensor data and device statuses to detect anomalies, triggering alerts and corrective actions when faults are identified. In our system, we also used WSN in 3; we describe by pseudocode how WSN works with our system.

Algorithm 3 Fault Identification in Home Automation

```
START
Initialize S = {s_1, s_2, ..., s_n} (sensors) and D = {d_1, d_2, ..., d_m} (devices)
Define normal operating ranges R(s_i) for s_i ∈ S
while System Active do
    Collect x_i from s_i ∈ S and status y_j from d_j ∈ D
    for s_i ∈ S and d_j ∈ D do
        if x_i ∉ R(s_i) or y_j = Failure then
            Log Fault(s_i or d_j) with timestamp t
            if Fault Type = Critical then
                Trigger alert system
            else
                Notify user if needed
            end if
        end if
    end for
end while
END
```

3.1.3. Wireless Sensor Network (WSN) Communication Model: The WSN Communication Model enables data transmission between sensor nodes and a central hub for efficient monitoring and control in IoT systems.

- Signal-to-Noise Ratio (SNR): The quality of WSN communication can be quantified by the signal-to-noise ratio (SNR) 9:

$$\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}} \tag{9}$$

Here, P_{signal} is the power of the received signal, and P_{noise} is the power of background noise.

- Data Rate and Bandwidth: The data rate R for WSN communication with bandwidth B and SNR can be represented using the Shannon-Hartley theorem 10:

$$R = B \log_2(1 + \text{SNR}) \tag{10}$$

Algorithm 4 WSN Operation in Home Automation System

START
Initialize $N = \{n_1, n_2, \ldots, n_k\}$ (WSN nodes with sensors) and C (central node)
Define transmission intervals Δt_i for $n_i \in N$
while System Active **do**
  for $n_i \in N$ **do**
    Collect sensor data $x_{i,j}$ for jth parameter (e.g., temperature, humidity)
    if $x_{i,j} > T_j$ (threshold) **then**
      Mark $x_{i,j}$ as "alert"
    end if
    Transmit $x_{i,j}$ to C
  end for
  At Central Node C**:**
  Receive $\{x_{i,j}\}$ from $n_i \in N$
  if any $x_{i,j}$ is marked as "alert" **then**
    Trigger action (e.g., alarm, notification)
  end if
  Send aggregated data to cloud/mobile app
  Log $\{x_{i,j}\}$ for future analysis
  for Control command u_k from Cloud/App **do**
    Execute u_k via appropriate n_i
  end for
end while
Deinitialize N and C
END

WSN is important for every IoT-based automation system. In our system, we also used WSN for better communication. In algorithm 4; we describe by a pseudocode how WSN works with our system.

WSN Scalability Testing and Performance Analysis: To evaluate the scalability and reliability of the Wireless Sensor Network (WSN) in a larger home or multi-story environment, we conducted a series of simulations measuring packet loss, signal strength, and latency as the number of nodes increased 2. These factors are critical in determining the network's efficiency, especially in setups with numerous IoT devices.

Here are three simulated graphs in Fig. 2 showing how our WSN performs with an increasing number of nodes:

1. Packet Loss vs. Number of Nodes: As the number of nodes increases, packet loss gradually increases due to network congestion and interference.
2. Signal Strength vs. Number of Nodes: Signal strength decreases as the network expands, particularly in multi-story buildings where obstacles affect transmission.
3. Latency vs. Number of Nodes: Network latency increases as more nodes are added, indicating potential delays in real-time communication.

3.1.4. Optimization of Sensor and Device Scheduling: Let $x_i(t)$ be a binary variable indicating whether device i is active (1) or inactive (0) at time t. To maximize efficiency, we can formulate an objective function to minimize active times while satisfying constraints for user comfort or security.

- Scheduling Optimization Function: It is a function that allocates tasks and resources efficiently over time to minimize energy consumption and maximize system performance 11.

$$\begin{aligned} &\min \sum_{i=1}^{N} \sum_{t=1}^{T} x_i(t) \cdot P_i \\ &\text{subject to:} \\ &\sum_{t=1}^{T} x_i(t) \cdot F_i(t) \geq C_i \end{aligned} \tag{11}$$

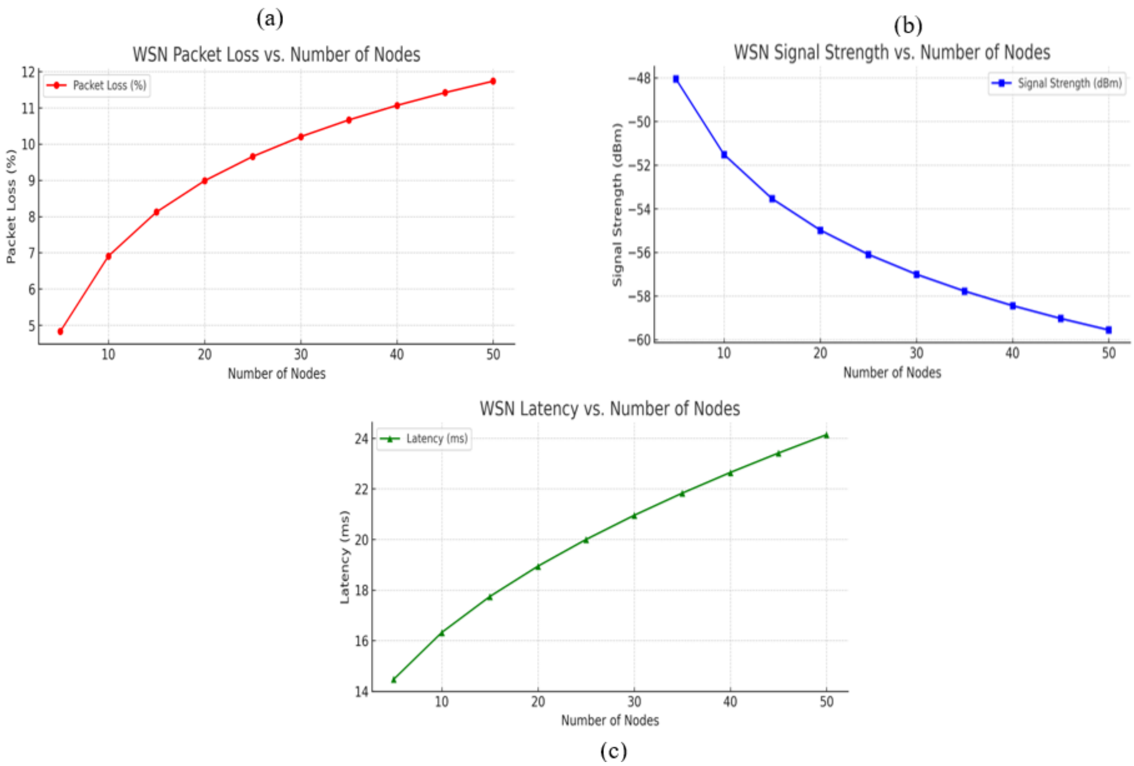

Figure 2. WSN Scalability Testing and Performance Analysis Graph

Here, $F_i(t)$ = functionality requirement for device i at time t, and C_i = cumulative requirement (e.g., total time the lights should be on during the evening).

3.1.5. System Reliability and Fault Probability: To model fault identification and reliability, we could use a probability-based approach.

- Probability of Fault Detection: Let P_d be the probability of detecting a fault correctly, P_f the probability of false fault detection, and n the total number of detection instances. The reliability R of the fault detection system can be expressed as 12:

$$R = \frac{n_d - n_f}{n} \tag{12}$$

Where n_d is the number of correctly detected faults, and n_f is the number of false detections.

- Mean Time Between Failures (MTBF): For a system with N components with failure rates, λ_i the mean time between failures (MTBF) can be estimated as 13:

$$\text{MTBF} = \frac{1}{\sum_{i=1}^{N} \lambda_i} \tag{13}$$

Where, N represents the total number of components in the system, λ_i is the failure rate of the i-th component.

3.1.6. Cybersecurity and Threat Mitigation: Since smart home systems connect to the internet, security is a major concern. Without proper protection, hackers could access devices, steal data, or even take control of home automation functions. To prevent this, our system includes multiple layers of security:

- Encrypted Communication: All data exchanged between devices and cloud servers is AES-encrypted (Advanced Encryption Standard) to prevent hacking. SSL/TLS encryption further protects communication, making it nearly impossible for attackers to intercept data.
- Secure Login and Access Control: We use OAuth 2.0 authentication to ensure that only authorized users can access the system. Additionally, we implement role-based access control (RBAC), which means different users have different permission levels, preventing unauthorized changes.
- Network Protection: To block cyberattacks like denial-of-service (DoS) or brute-force login attempts, we use firewall rules, rate limiting, and secure boot features. This ensures that hackers cannot overload the system or install malicious code.
- Threat Detection: If an unauthorized access attempt is detected, the system immediately sends an alert via email or mobile app, allowing the user to take action.
- Regular Updates: Since security threats evolve, we provide over-the-air (OTA) software updates, ensuring vulnerabilities are patched before they become a problem.

The following table 2 summarizes common cyber threats and the mitigation strategies implemented in the system:

Table 2. Cybersecurity Threats and Mitigation Strategies

Cyber Threat	**Potential Impact**	**Mitigation Strategy**
Unauthorized Access	System control compromise	AES encryption, OAuth 2.0, RBAC
Man-in-the-Middle Attack	Data interception	SSL/TLS encryption, secure API endpoints
Brute Force Attacks	Password guessing	Rate limiting, strong password policies
Denial-of-Service (DoS)	System slowdown/crash	Firewall rules, anomaly detection, traffic filtering
Firmware Tampering	Unauthorized code execution	Secure boot, OTA firmware verification
Data Interception	Personal data leakage	End-to-end encryption, periodic security audits

3.2. *Collecting of Hardware Requirements*

Our system requires several key hardware components to function effectively. Table 3 outlines the specific roles and functionalities of each hardware component within our IoT-enabled home.

3.3. *Arrangement of Software Requirements*

3.3.1. Arduino IDE: The Arduino IDE supports Linux, Mac OS X, and Windows, facilitating programming in C and C++. Programs, known as sketches, are created and uploaded to Arduino boards via the IDE for execution [41, 42].

3.3.2. Blynk Mobile Application: Blynk is a versatile software suite that allows users to connect hardware to the cloud, enabling the creation of iOS, Android, and web applications for remote management. It supports everything from personal IoT projects to large-scale commercial deployments, offering real-time data analysis, remote control, notifications, and more [43].

3.3.3. Adafruit IFTTT: Adafruit's integration with IFTTT automates actions between connected devices and various apps. It enables voice commands and customized triggers, allowing for seamless control of IoT devices. This integration simplifies complex tasks and enhances the functionality of IoT projects by connecting multiple platforms effortlessly [44].

Table 3. Functionalities of Components in the Home Automation System

Component	Functionality
Arduino Uno	Manages door lock operation via the servo motor, handles gas and humidity sensor data, and controls the buzzer and LEDs for security alerts.
NodeMCU ESP8266	Enables wireless communication, sends real-time sensor data to the Blynk app, and processes voice commands from Google Assistant for controlling lights and fans.
RFID Scanner	Authenticates user access to the door. Activates the servo motor for door unlocking and triggers LEDs and a buzzer based on access status.
Servo Motor	It controls the locking mechanism of the door, which is activated by Arduino Uno upon successful RFID authentication. Also controls window closing and solar rotation.
MQ2 Gas Sensor	Monitors gas levels in the home. Triggers a buzzer and sends an email alert if gas levels exceed the threshold.
DHT-11 Sensor	Measures temperature and humidity, providing real-time data to the Arduino Uno for display on the LCD and Blynk app.
LCD Display	Shows real-time gas levels, temperature, and humidity data received from the sensors.
Rain Sensor	Detects rainfall and automatically signals the servo motor to close the window.
Ultrasonic Sensor	Monitors water levels in the tank. Controls the water pump to maintain optimal levels.
Water Pump	Activated by the ultrasonic sensor to maintain water levels in the tank, with manual control via the Blynk app.
Solar Panel	Charges the system's battery. The panel's angle is adjusted by a servo motor based on LDR sensor readings to maximize energy efficiency.
LDR Sensors	Continuously monitor sunlight direction and intensity, guiding the servo motor to optimize the solar panel's alignment.

3.3.4. Google Assistant: Google Assistant is a virtual assistant software application developed by Google that is primarily available for home automation and mobile devices. Based on artificial intelligence, The Google Assistant can engage in two-way conversations, unlike the company's previous virtual assistant, Google Now [45, 46].

3.4. Cost Analysis

The total cost of the proposed system is approximately 24,800 BDT, equivalent to approximately 202.64 USD (based on an exchange rate of 1 USD = 122.38 BDT). Table 4 provides a detailed breakdown of the costs of components, which highlights the affordability of the system.

Compared to other commercial home automation systems, which typically start at 24,800 BDT (202.64 USD), the proposed system offers a substantial cost advantage. By utilizing locally sourced components and open source software, the system ensures accessibility and affordability, making it an excellent choice for budget conscious users.

3.5. Working Procedure of System Model

Our IoT-enabled home automation system is well-suited for managing home security, monitoring environmental conditions, and pushing notifications in real time through a mobile application or via voice control. It initializes all the connected sensors and actuators, such as RFID, servo motor, gas sensor, temperature-humidity sensor, ultrasonic range sensor, rain sensor, and LCD. When a valid RFID tag will be scanned at the entrance, the servo motor unlocks to allow you, A green LED turns on with a buzzer, and immediate feedback is provided. The door will not open if an unauthorized tag is scanned; in this case, the yellow LED lights up with the buzzer on, and the lock remains closed, ensuring better home security.

On the other hand, the system continuously monitors the environment of the home with a single unified system. The temperature and humidity levels are sensed by the DHT11 sensor, whereas gas levels that are hazardous can be detected via the MQ2 sensor. The display of this data in real-time on the LCD screen, as well as forwarded to a

Table 4. Cost Analysis Table

Component	**Cost (BDT)**
Arduino Uno	1,000
NodeMCU ESP8266	500
RFID Scanner	1,200
Servo Motor	400
MQ2 Gas Sensor	300
DHT-11 Sensor	250
LCD Display	600
Rain Sensor	350
Ultrasonic Sensor	300
Water Pump	800
Solar Panel	3,000
LDR Sensors	100
Power Supply 12V 55AH Battery	11,000
Maintanance Cost	5,000
Total	**24,800**

Blynk mobile app, makes it possible for them to be aware of what is happening at home even when users are not there. If gas leakage is detected by the sensor, then the system sends an alert mail to the user.

The system includes a rain sensor that identifies when it is raining. Should the rain sensor be triggered by rainfall, windows will close automatically to prevent water from coming inside and covering up all of the indoor sections. Voice control enhances user convenience, allowing for hands-free management of lights, fans, and other devices through simple voice commands using the Adafruit IFTTT application. For instance, saying "Turn on the light" will activate the light, and the Blynk app will confirm the command's execution in real-time. The system is powered by a solar panel, ensuring continuous operation even during power outages and providing an energy-efficient solution for modern smart homes. The workflow and interactions of these components are illustrated in Fig. 3, offering a comprehensive overview of the system's functionality.

Here, we describe every subsystem of our system.

- Door Lock Subsystem: Here in figure 4 is our home automation system's first part. In this section, we used passive tag-based RFID, where the tag is powered by a scanner based on Faraday's law of electromagnetic induction. The scanner creates an electromagnetic field. Once powered, the tag sends its data back to the reader by modifying the magnetic field. This process follows the rule in equation 14:

$$V = N \cdot \frac{d\Phi}{dt}, \quad \Phi = \mu \cdot H \cdot A \tag{14}$$

  RFID (Radio Frequency Identification) has two types of tags: one is the correct tag for an authentic user only, and all other tags are wrong. The RFID scanner is always scanning, and when an authentic user scans the right tag, then the green LED is on and the buzzer buzzes with the door opening by the servo motor successfully. Other hands, when a wrong user comes and scans the wrong tag that is not registered, then the yellow LED is on and the buzzer is buzzing for alarming. Finally, an RFID-based door system secures access by allowing only authorized tags to unlock the door through encrypted communication and verification, such as using AES encryption shown in 15:

$$C = E_k(M) \tag{15}$$

  where C is the ciphertext, M is the message, and E_k is the encryption function with key k.
- Home Parameter Monitoring Subsystem: In fig 5, shows the home parameter monitoring subsystem features the DHT11 and MQ2 gas sensors connected to the ESP8266, with data displayed on an I2C LCD and

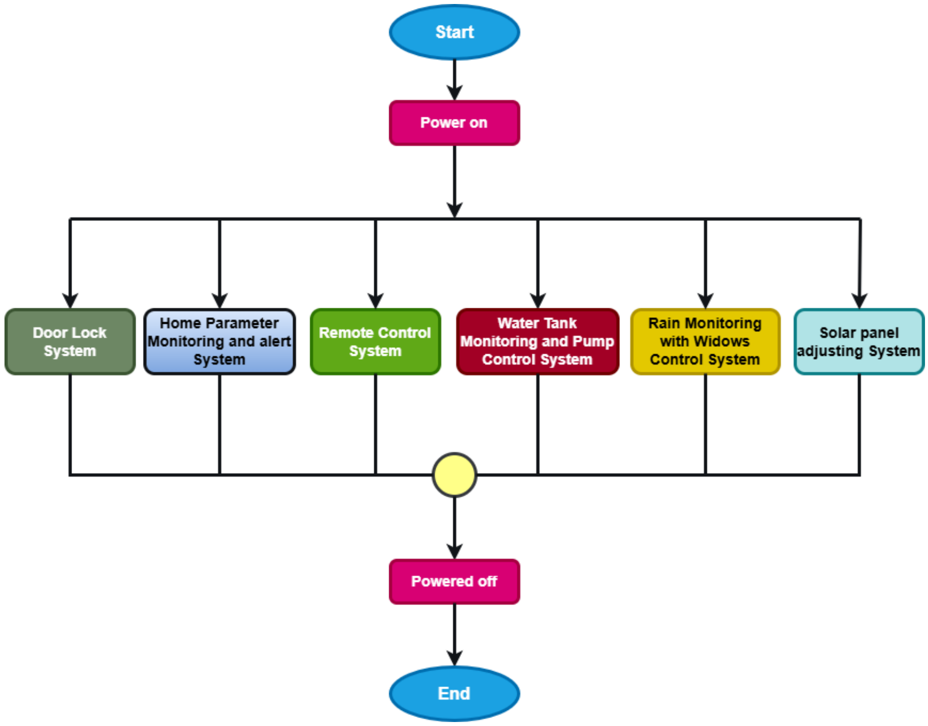

Figure 3. Working Flow of the System

the Blynk app. The DHT11 monitors the home's humidity and temperature, while the MQ2 detects gas leakage. If gas leakage is detected, the system triggers a buzzer, sends an encrypted email to the owner, and updates the Blynk app. The sensors work by measuring humidity and temperature (DHT11) and detecting gas concentration through electrical resistance changes (MQ2). To ensure security, the ESP8266 uses AES 15 encryption for email notifications ($C = E_k(M)$), SSL/TLS for secure communication with the email server, and OAuth for authentication, ensuring that only authorized devices and users can send notifications. Additionally, all communication is encrypted, and secure Wi-Fi credentials are used to protect the system from unauthorized access.

- Remote Control Subsystem: Here in fig 6 shows the remote control home parameter monitoring system allows control of home parameters in two ways: through the Blynk app for fans and lights and via voice commands using Google Assistant. The lights and fans are connected to the ESP8266 through relays that act as switches. To ensure security, the Blynk app uses end-to-end encryption for communication with the ESP8266, while voice control via Google Assistant is secured using OAuth 2.0. Here, the access token is generated using the equation in 16:

$$T_{access} = E(H(C_{id} + C_{secret} + A_{code} + R_{url})) \tag{16}$$

where C_{id} is the client ID, C_{secret} is the client secret, A_{code} is the authorization code, R_{url} is the redirect URL, H is a hashing function, and E is an encryption function, ensuring only authorized users can access the system. Additionally, SSL/TLS encryption secures communication between the ESP8266 and external services, and Wi-Fi credentials are safeguarded to prevent unauthorized access.

- Water Tank Monitoring and Pump Control Subsystem: In Fig. 7 shows, the water tank monitoring and controlling system uses pump and a sonar sensor. The Pump is connected to the ESP8266 through a relay module, while the ultrasonic sensor is connected to the ESP8266 via its digital input pins for distance measurement. An ultrasonic sensor measures the water level by calculating the distance to the water surface.

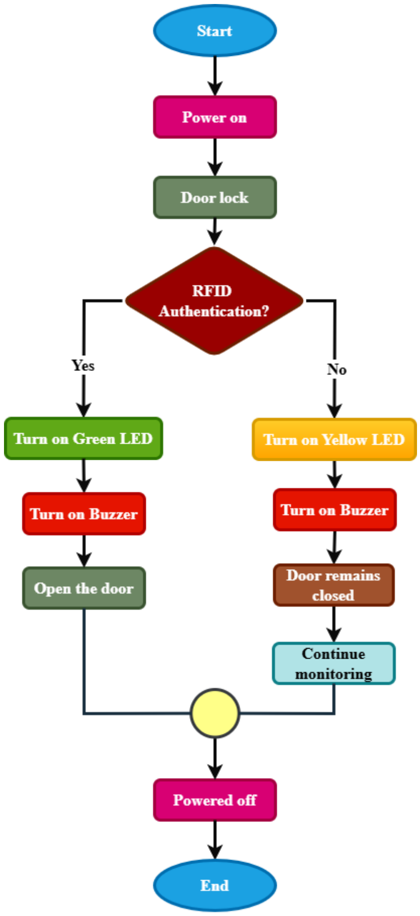

Figure 4. Working Flow of the Door Lock System

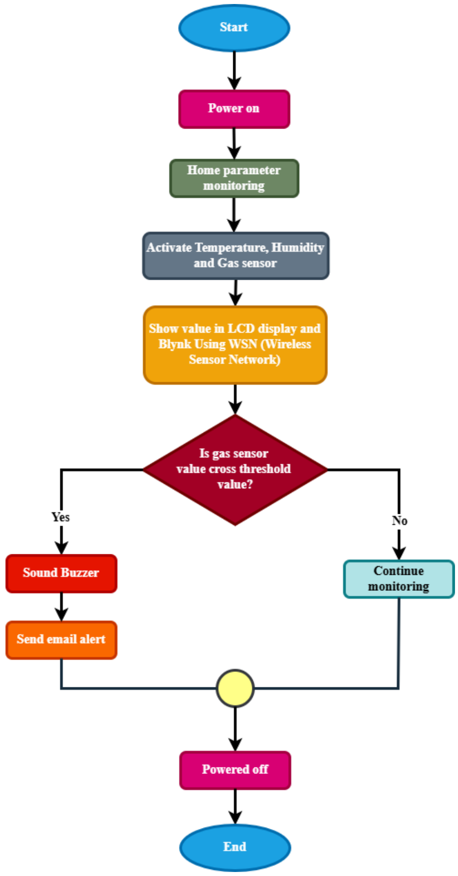

Figure 5. Working Flow of the Home Parameter Monitoring System

The measured water level is displayed in real-time on the Blynk app via a wireless sensor network (WSN). The pump operates automatically: If the water level is below a specified height (for example, 20 cm from the sensor), the pump turns on and stops when the water level is adequate. Users can also manually control the pump through a virtual switch in the Blynk app. To ensure security, the system uses SSL / TLS encryption for communication between the ESP8266 and the Blynk app. Furthermore, manual pump control is protected through OAuth 2.0-based user authentication. The access token for authentication is generated using $T_{access} = E(H(C_{id} + C_{secret} + A_{code} + R_{url}))$, where C_{id} is the client ID, C_{secret} is the client secret, A_{code} is the authorization code, R_{url} is the redirect URL, H is a hashing function, and E is an encryption function. This secure and automated system ensures efficient and safe monitoring of water level and pump control.

- Solar Panel Subsystem: The most interesting part is shows in fig 8; the solar panel subsystem plays a vital role in powering the entire home automation system. A solar panel is connected to an Arduino Uno, which acts as the primary microcontroller. To maximize sunlight utilization, the solar panel is mounted on a servo motor controlled by Arduino Uno. Light-dependent resistors (LDRs) are placed on different sides of the panel to detect sunlight intensity. Based on the LDR readings, the Arduino adjusts the servo motor to position the panel toward the direction with maximum sunlight, such as east, south, or west. To ensure the system's security, the Arduino Uno validates motor control commands using a checksum verification method 17:

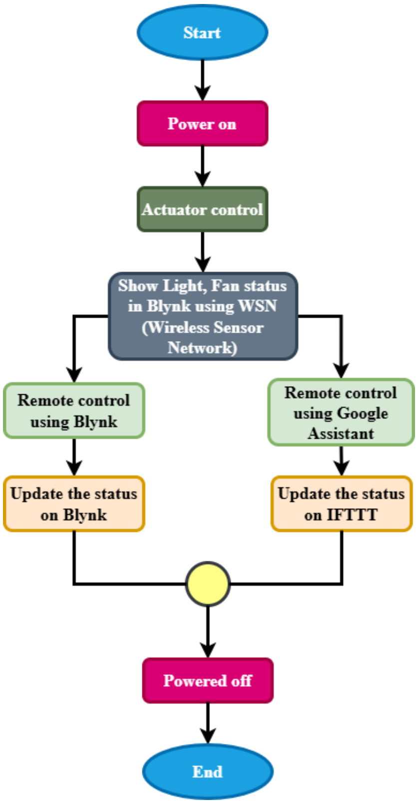

Figure 6. Working Flow of the Home Remote Control System

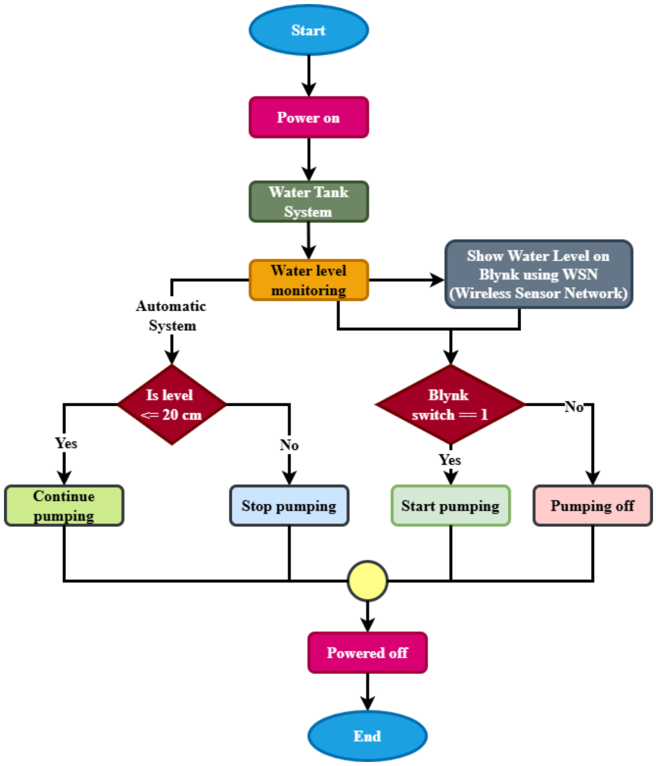

Figure 7. Working Flow of the Water Tank Monitoring and Pump Control System

$$C = \sum_{i=1}^{n} D_i \mod 256 \tag{17}$$

where C is the checksum, D_i are the data bytes in the command, and n is the number of bytes. This ensures that only valid instructions are executed, reducing the risk of unauthorized or corrupted commands. Additionally, the operation of the servo motor is monitored with position feedback, and unauthorized manual adjustments are detected and logged. To further enhance security, all system updates and control commands are authenticated locally via physical access to the Arduino, ensuring no external tampering or wireless interference. Power from the solar panel is also monitored using a voltage sensor to protect the system from overcharging or power surges, ensuring safe and uninterrupted operation.

- Rain Monitoring with Windows Control System: In fig 9 shown, the rain monitoring subsystem integrates an automatic window control system to protect the home's interior during rainfall. A rain sensor, placed on the roof, detects rainfall and sends a signal to an Arduino Uno microcontroller. The microcontroller then controls servo motors connected to the windows, automatically rotating them to close the windows when rain is detected. To ensure system security and reliability, the commands sent to the servo motors are validated using a hashed message authentication code (HMAC) to prevent unauthorized or corrupted instructions. The security can be represented as 18:

$$H = \text{HMAC}(K, M) \tag{18}$$

where H is the hash, K is the secret key shared between the sensor and the Arduino, and M is the message (command). This ensures that only commands originating from the rain sensor and validated by the Arduino are executed. Additionally, the rain sensor readings are debounced using a time threshold to filter out false triggers, and servo motor feedback is monitored to verify successful operation. These layers of security ensure reliable and secure automatic window control during rainfall.

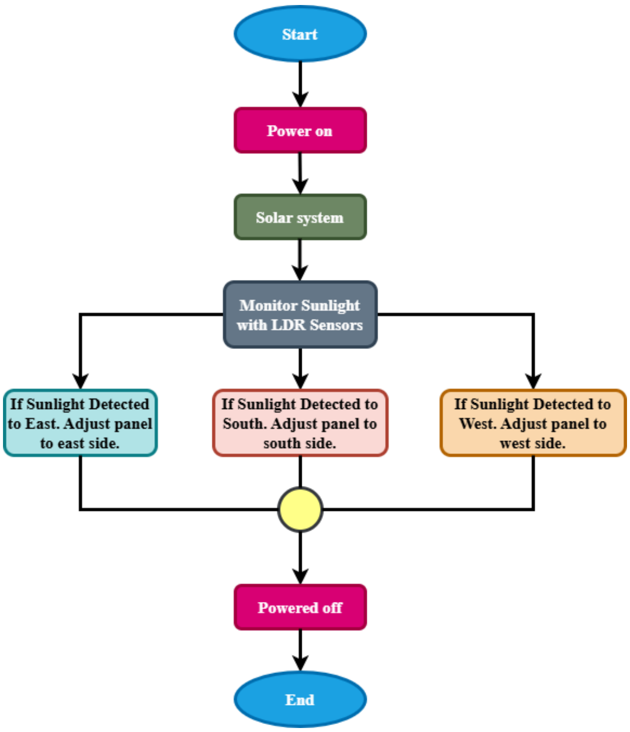

Figure 8. Working Flow of the Solar panel adjusting System

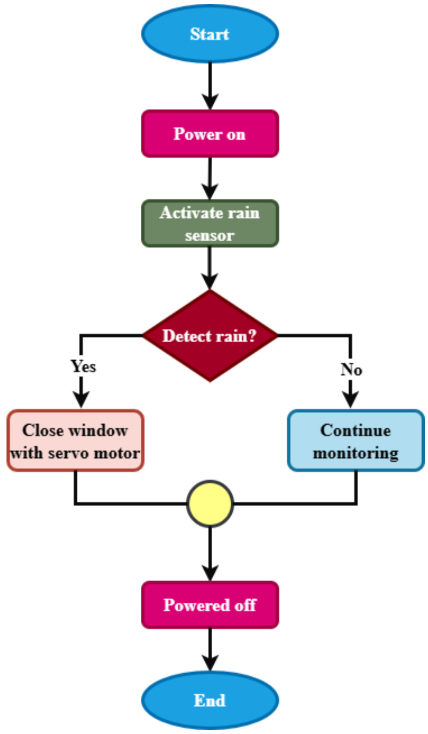

Figure 9. Working Flow of the Rain Monitoring with Widows Control System

4. Result Analysis and Performance Measurement

4.1. Performance Analysis

4.1.1. Performance Analysis of RFID Sensor for Secure Entry: Fig. 10(a), the RFID sensor is being tested to allow secure entry at the front door. The sensor showed a high degree of correctness and stability in confirming legal user identities after being evaluated repeatedly over the course of several days. Under this configuration, the system was tested under different conditions, like various RFID tag positions and distances. The sensor works with up to 5 cm accuracy and a success rate over 95% from the reader; on the other hand, its performance decreases a bit when not properly aligned with the RFID tag presented to the reader or when attempting it again too fast. This is a demonstration of the high reliability, but also that the RFID sensor performance might be critically influenced by tag positioning.

To represent the performance of the RFID sensor mathematically, the success rate S can be expressed as a function of the distance d and alignment θ in 19:

$$S(d, \theta) = S_{\text{max}} \cdot e^{-\alpha d} \cdot \cos^2(\theta) \tag{19}$$

Here, S_{max} represents the maximum success rate (e.g., 95% or 0.95). The parameter d denotes the distance between the RFID tag and the reader, while α is the decay constant, accounting for sensitivity to distance. The angle θ indicates the misalignment between the tag and the reader. The term $\cos^2(\theta)$ reduces the success rate

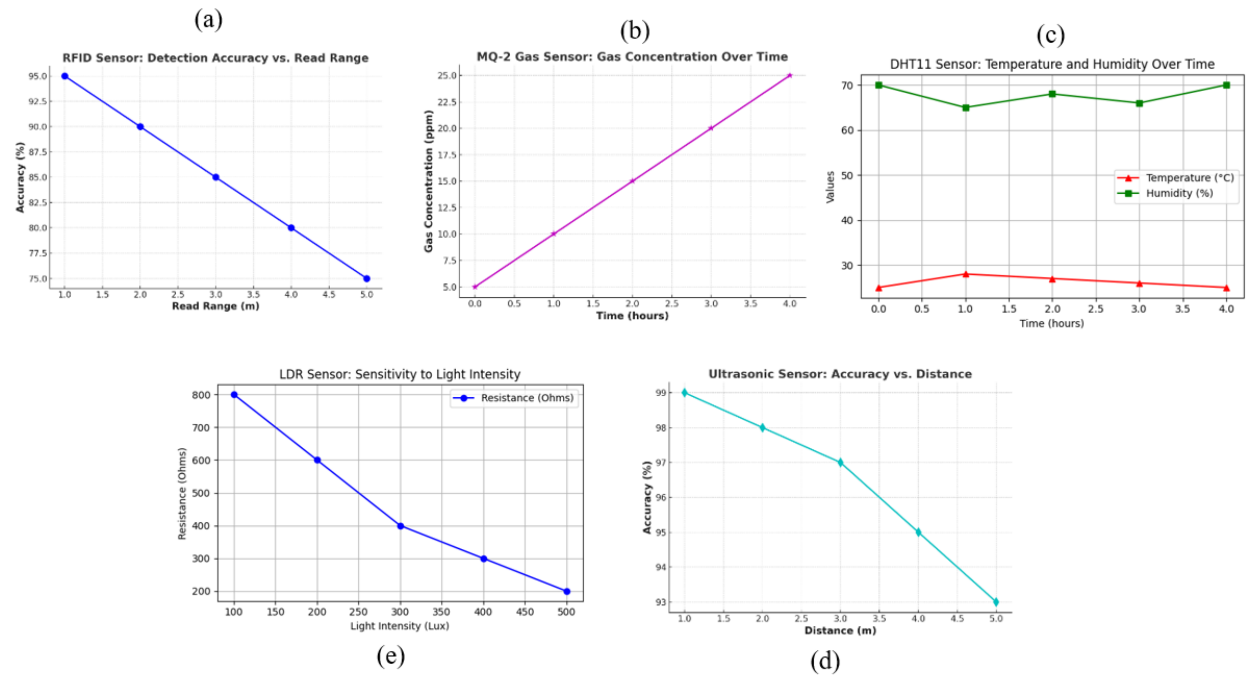

Figure 10. (a) RFID Sensor Detection Accuracy vs. Read Range, (b) MQ-2 Gas Sensor Gas Concentration Over Time, (c) Ultrasonic Sensor Accuracy vs. Distance, (d) LDR Sensor Sensitivity to Light Intensity, (e) Temperature and Humidity Over Time

based on the misalignment, ensuring the equation reflects real-world performance trends. This model captures the decrease in performance with increasing distance and misalignment.

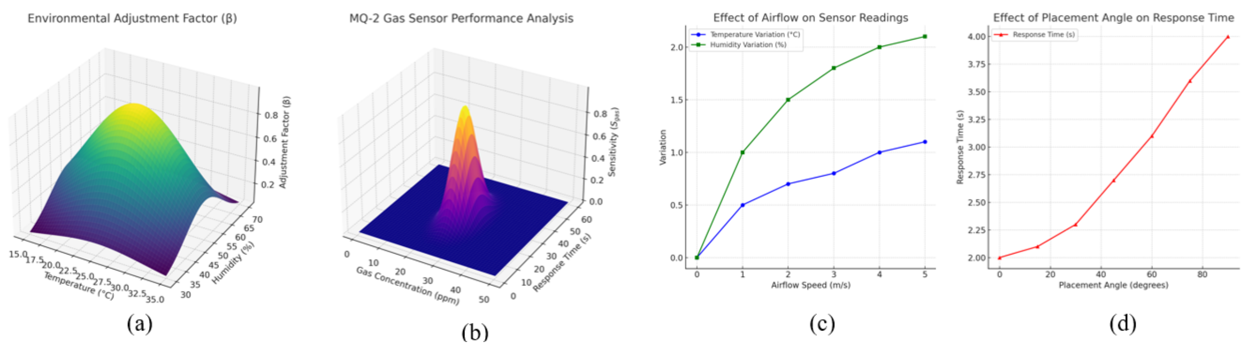

Figure 11. (a) Environmental Adjustment Factor (β) Considering Temperature and Humidity Variations, (b) Performance Analysis of MQ-2 Gas Sensor for Various Gas Concentrations and Response Times, (c) Effect of airflow on DHT11 readings, (d) DHT11 sensor accuracy under different placement angles

To enhance the analysis of the RFID sensor performance, we incorporated environmental factors, specifically temperature (T) and humidity (H), into the success rate model. The environmental adjustment factor, β, is modeled as equation 20:

$$\beta(T, H) = \exp\left(-\gamma_1(T - T_0)^2 - \gamma_2(H - H_0)^2\right), \tag{20}$$

where T_0 and H_0 represent optimal temperature and humidity, respectively, while γ_1 and γ_2 are sensitivity constants. The overall success rate of the RFID sensor can then be expressed as equation 21:

$$S(d, \theta, T, H) = S_{\text{max}} \cdot \beta(T, H) \cdot e^{-\alpha d} \cdot \cos^2(\theta). \tag{21}$$

Figure 11(a) illustrates the influence of temperature and humidity on β, highlighting that optimal environmental conditions significantly enhance performance. This expanded model provides a comprehensive representation of real-world performance, accounting for both physical and environmental factors.

4.1.2. Performance Analysis of MQ-2 Gas Sensor: For the home environment testing of all gases, the MQ-2 gas sensor was selected. Different gases, such as smoke, LPG, methane, and alcohol, were tested using a sensor for a few days to check the sensitivity of sensors shown in Fig. 10(b). The results indicated that the sensor is most sensitive to LPG and smoke, even inducing weak concentrations. The sensor's performance was consistent with all gas types, with a response time between a few seconds and one minute based on the managed concentration. Nonetheless, deployment of the sensor might be influenced by high humidity and temperature, for which calibration is needed under such conditions. The performance of the MQ-2 gas sensor was analyzed for home environments by testing various gases, including smoke, LPG, methane, and alcohol, over several days, as shown in equation 22.

$$S_{\text{gas}} = S_{\text{max}} \cdot e^{-\beta C} \cdot T_{\text{resp}} \tag{22}$$

Here, S_{gas} represents the sensor's sensitivity, S_{max} is the maximum sensitivity (e.g., to LPG and smoke), β accounts for the effect of gas concentration C, and T_{resp} is the response time (a few seconds to one minute). The results show a high sensitivity to weak concentrations of LPG and smoke, with consistent performance across gases. Calibration is needed for high humidity or temperature conditions.

Fig. 11(b) illustrates the sensitivity of the MQ-2 gas sensor across different gas concentrations and its response time. The sensor demonstrates consistent performance, particularly for LPG and smoke, even at low concentrations.

4.1.3. Performance Analysis of DHT11 Temperature and Humidity Sensor: To test the accuracy of monitoring temperature and humidity inside our home, we used a DHT11 sensor. Readings collected over a period of four days indicate the sensor captured temperatures that oscillated between 20°C and 35°C, accompanied by corresponding humidity levels ranging from 40% to around up to more than 70%, which is shown in 10(c). The sensor was sensitive to changes in the environment, such as the operation of HVAC or the opening of windows. Data showed that the sensor was consistently accurate, with little variation in room temperature. The accuracy of the sensor can be slightly affected by sudden temperature changes because it tends to vacillate a bit before stabilizing its readings.

$$A_{\text{sensor}} = f(T, H) \cdot e^{-\gamma \Delta T} \tag{23}$$

Here,in equation 23, A_{sensor} represents the sensor's accuracy, $f(T, H)$ denotes the relationship between temperature T (20°C–35°C) and humidity H (40%–70%), and γ accounts for sensitivity to sudden temperature changes ΔT. The sensor showed high accuracy, with stable readings, but slight instability occurred during abrupt environmental changes.

To further expand the analysis, we investigated the influence of factors such as airflow, sensor placement, and long-term stability. Figure 11(c) & (d) shows additional data trends collected by varying airflow conditions and placement angles. These results suggest that airflow-induced variations were minor, while sensor placement significantly impacted response time. The performance remained consistent over the prolonged operation, with no significant sensor drift observed. In conclusion, the DHT11 sensor demonstrated reliable performance in monitoring indoor temperature and humidity, with high sensitivity to environmental changes and stable operation over time. However, proper calibration and placement are crucial for optimal results.

4.1.4. Performance Analysis of Ultrasonic Sensor for Water Level Monitoring: The water level in the smart tank was monitored as shown in 10(d) using an ultrasonic sensor. For four days, the sensor did a great job of measuring if there was water and how deep it was and whether or not it needed to fill up the tank with fresh rainwater via pump. The sensor operated in a relatively consistent manner and measured water levels with an error margin of less than 1%. But, in fact, the sensor accuracy was slightly lower when dealing with turbulent water surfaces and strong motion of them. The data also showed that the sensor was most accurate when installed at a specific height and angle, hinting again at the importance of careful setup.

$$E_{\text{sensor}} = \frac{|L_{\text{measured}} - L_{\text{actual}}|}{L_{\text{actual}}} \cdot 100 \tag{24}$$

Here, in above equation 24, E_{sensor} represents the error margin, L_{measured} is the measured water level, and L_{actual} is the actual water level. The sensor showed high accuracy, with an error margin of less than 1%. However, its accuracy decreased with turbulent water surfaces and strong motion. The sensor performed best when installed at a specific height and angle, emphasizing the importance of proper setup for optimal performance.

4.1.5. Performance Analysis of LDR Sensors in Solar Tracking System: This solar tracking system includes two LDR sensors to adjust the direction of light falling over a surface and, accordingly, its angle. This evaluation was carried out for four days to check the performance of these sensors shown in Fig. 10(e). Through the above system, it was able to capture maximum sunlight through solar sensors, which we implemented, and LDR detected light intensity on a real-time basis panel position is changed. This test was to validate the fact that LDR sensors would respond fast enough for changes in light intensity to enable proper alignment with the sun. On the other hand, when sunlight was very low or if it got cloudy outside, the sensors had more trouble tracking that sun location, so a backup energy source is still highly needed for such moments.

The performance of the LDR sensors in the solar tracking system was evaluated over four days to monitor the alignment with sunlight as shown in equation 25.

$$I_{\text{LDR}} = I_{\max} \cdot e^{-\lambda \Delta\theta} \tag{25}$$

Here, I_{LDR} represents the light intensity detected by the LDR sensors, $I_{\max}$ is the maximum light intensity, and λ is the sensitivity constant related to the angle change $\Delta\theta$. The LDR sensors efficiently adjusted the solar panel position to capture maximum sunlight under normal conditions. However, when sunlight was low or cloudy, the sensors had difficulty tracking the sun, highlighting the need for a backup energy source in such conditions.

4.1.6. Performance Analysis of Rain Sensor: The rain sensor was tested to see if it carried out detected rainfall and automatically closed, thereby protecting the interior of the house from being found above. Next came the tests with different magnitudes of intensity of rainfall. The data revealed that the sensor could even detect light rain and would respond by closing the window after sensing only a few seconds of liquid. The higher sensitivity of the sensor prompts closure even in light drizzle, covering for water damage. Inversely, however, the sensor can produce false positives in high humidity conditions without rain, and consideration would have required this deployment.

The performance of the rain sensor was evaluated for detecting rainfall and automatically closing windows to protect the interior as shown in equation 26.

$$T_{\text{response}} = \frac{K}{I_{\text{rain}}} \cdot e^{-\mu H} \tag{26}$$

Here, T_{response} represents the sensor's response time to rainfall, K is a constant, I_{rain} is the intensity of rainfall, and μ is the sensitivity to humidity H. The sensor successfully detected even light rain and responded quickly by closing windows after sensing minimal liquid. However, high humidity conditions without rain led to false positives, suggesting the need for further calibration to reduce such occurrences.

4.2. Real-time Analysis

Fig. 12 presents the key features incorporated into our home automation system. The system is designed to prioritize functionality and ease of use while maintaining an advanced technological framework.

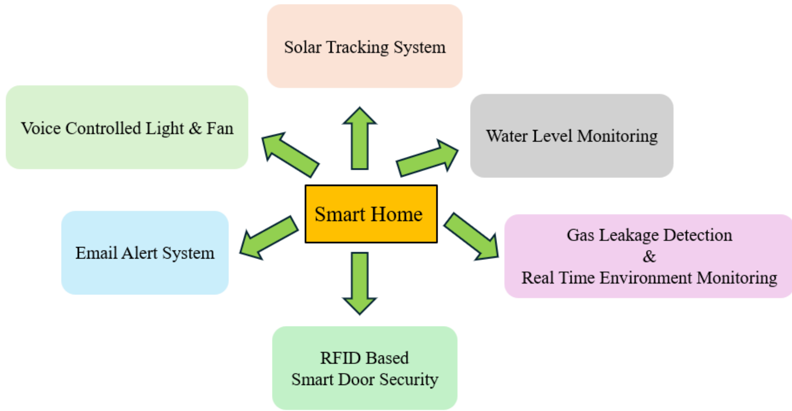

Figure 12. (a) Home Automation All Features Block Diagram

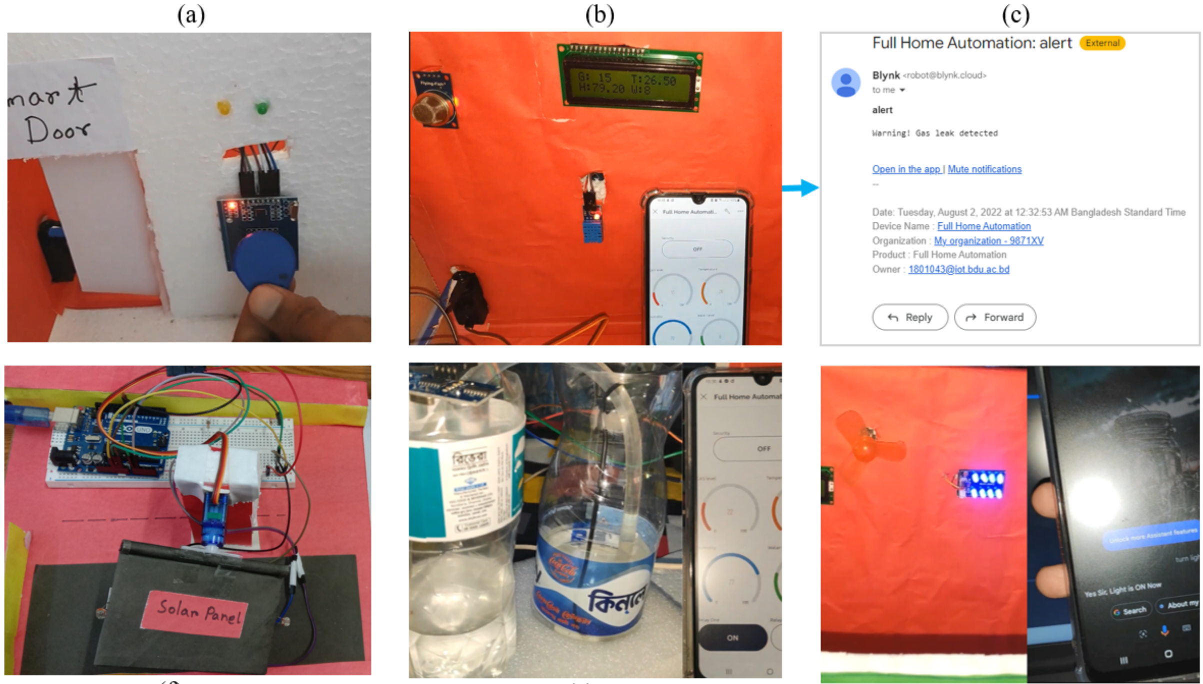

Figure 13. (a) RFID Based Smart Door Security, (b) Gas Leakage Detection and Real Time Environment Monitoring, (c) Mail Alert From Blynk, (d) Voice Controlled Light and Fan, (e) Water Level Monitoring, (f) Solar Tracking System

4.2.1. RFID Based Smart Door Security: Fig. 13(a) is the output of an RFID-based smart door lock system. The system has an RFID reader that works with the RFID tags to allow or deny access. A green LED is lit when a working RFID tag is brought near to the reader; it informs that RFID authentication has been done successfully and the door will be opened by a rotating servo motor. However, with the use of an incorrect or unauthorized tag, the door stays locked, and a second LED will light up, alarming the buzzer to signal that access is denied.

4.2.2. Gas Leakage Detection: This Fig. 13(b) shows smart home automation, which helps us keep track of our environmental conditions, including security, monitoring all the while in real-time, and alerting. There is a gas sensor named MQ-2 in the system to catch leakages, and if the level of gas crosses that predetermined limit, it will start alarming as well as send an email alert to the user, which is shown in Fig. 13(c).

4.2.3. Real Time Environment Monitoring: The system also monitors temperature and humidity by a sensor (DHT11) shown in Fig. 13(b), which updates information on the Blynk smartphone app as well as the LCD display. It can be used for remote monitoring and management of home conditions, increasing safety and comfort.

4.2.4. Voice Controlled Light and Fan: Fig. 13(d) shows an implementation of voice-controlled functionality with Adafruit IFTTT and Google Assistant. The appropriate IoT devices are turned on or off by issuing voice commands using Google Assistant, such as "Turn Light on" or "Turn Fan on." The system adeptly follows voice command inputs to manage such devices, which, when taken into account with Adafruit's IFTTT platform, essentially establishes how smoothly and perfectly an IoT device can be integrated with samples of voice recognition in smart homes for home automation.

4.2.5. Water Level Monitoring: Fig. 13(e) displays smart water management, which can monitor the level of the tank with the help of an ultrasonic sensor. A major property and recommendation feature is that it keeps a log of the water level as measured from sensor to topmost portion. So, if that water tank level goes below a certain lower limit, the system will start the water pump automatically, and it means to refill the storage of water. On the other hand, if the water level has reached the maximum boundary, then the pump will switch it off so that there is no more inflow. Also, it has been interfaced with the Blynk app for a real-time view of the water level and manual control over the pump on our smartphone. This type of setup ensures better water management as it automatically refills and can be controlled remotely.

4.2.6. Rain Detection Based Window Shut Down: The rain sensor itself works by detecting moisture and closing off the windows when it senses some water drops, which then activates a servo motor (also part of this system). With this mechanism, we can protect the indoor area from rain. The servo motor moves quickly to close the window, which shuts off potential water penetration and ensures that no one at home stays dry while this dries out. This automatic feature strengthens system efficiency.

4.2.7. Solar Tracking System: Fig. 13(f) is an image of a solar panel system where the sensor takes a light-dependent resistor, and its positioning can be done with moisture if it detects more sunlight using LDR so that the servo motor will automatically adjust angle for energy absorption. It achieves the most effective collection of solar energy by following the sun in rotation. The setup was a practical implementation of the automatic solar tracking used for keeping their solar panel aligned with the sun throughout the day to get an increased amount of output energy at the end.

5. Result Validation and Comparative Analysis

We conducted thorough examinations of smart home sensors across different environmental variables to benchmark their performance capabilities while assessing both reliability factors. With RFID technology, the secure entry sensor exhibited a 95% recognition accuracy at a reading distance of 5 centimeters, which worked reliably under all tested environmental circumstances. The accuracy, response time, and error margins for key sensors are shown in Fig. 14.

The experimental results highlight the significant improvements introduced by our system. The system ensures high sensor reliability, with error margins remaining below 2.5%, confirming its precision in environmental monitoring and automation. These findings collectively validate the robustness, efficiency, and reliability of our proposed home automation system, positioning it as a superior alternative to existing solutions. The error margins are within acceptable industry limits for home automation applications. The slight deviations in the LDR sensor readings are due to fluctuating light conditions, while the gas sensor showed higher variance under high humidity environments. By measuring environmental parameters, the DHT11 sensor demonstrated precise responses to

Figure 14. (a) Sensor Performance and Error Margins

sudden changes in temperature and humidity. Long-lasting tests must be conducted to both prove oppositional reliability and maintain performance stability for extended periods. The ultrasonic sensor provided highly accurate water level measurements, although its performance declined when installation resulted in problematic positioning or unsteady water flow. Regular maintenance in combination with proper installation training would solve these difficulties. LDR sensors demonstrated adept performance in sunlight tracking but showed reduced efficiency when conditions became dull and overcast. To mitigate the weather dependency of the solar tracking system, we can go for hybrid energy systems that incorporate grid electricity and battery backup as an approach to maintain continuity during harsh weather conditions. The rain sensor functioned adequately to recognize precipitation intensity, yet its detection mechanism confused high humidity with rainy conditions on specific occasions. Improved sensor design to distinguish between humidity and rain will fix this problem. Fig. 15 demonstrates how sensors work based

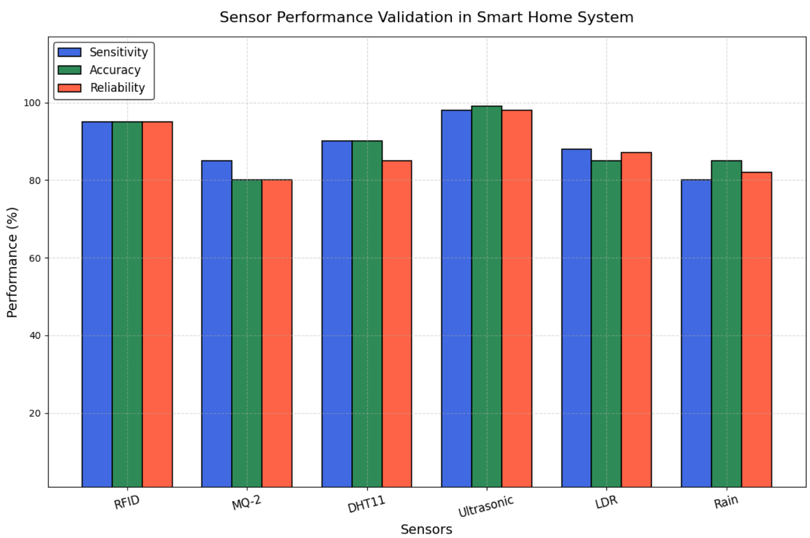

Figure 15. (a) Sensor Performance Validation

on their measurement precision and durability. The chart compares how well RFID tags and sensing components especially MQ-2, DHT11, Ultrasonic, LDR, and Rain work together in smart home applications. Symptoms of every sensor - sensitivity, accuracy, and dependability - appear in different color charts for clear performance reviews under distinct scenarios.

6. Discussion, Limitations, Challenges, and Future Work

This IoT-based home automation system provides a major contribution to the field of smart homes, presenting several features that work together to improve security, energy efficiency, and usability for users. It integrates RFID-based access control, live monitoring of environmental conditions, energy-efficient solar tracking, and remote operation via mobile and voice commands. By employing WSN and IoT capabilities, the system gives seamless connectivity to the different components of the system, which provides an intelligent home automation system. However, there are still limitations and challenges that need to be addressed to enable the system to be more reliable, scalable, and sustainable in the long run.

Among the main disadvantages of the system is its reliance on the internet for remote work. Although an internet-based system can allow a customer to access and control their system from practically anywhere, these types of wireless control systems fall down in areas where 4G or 5G network coverage is spotty or non-existent. In some scenarios, system functionality can be limited, especially for those functions relying on real-time data transmission and cloud-based processing. To address this problem, one is offline mode, which provides local data storage, as well as core functions, such as door access control, gas leak detection, and automatic window closure, which can still work independently. In addition, it brings together local wireless communication such as Bluetooth and ZigBee to enable in-home control without a constant internet version. These changes enhance the reliability of the system in challenging network conditions, like under high latency or frequent changes in network connectivity. A further issue is that sensors require constant recalibration to operate within an acceptable margin of error. It can also lead to drift in parameters like the readings of temperature, humidity, gas detection, water level monitoring, etc. Recalibrating the sensors manually can be complicated and time-consuming for users not familiar with the technical aspect. The system utilizes automated self-calibration mechanisms that calibrate sensor thresholds from historical data trends to mitigate this issue. AI-based predictive maintenance has also been suggested to identify sensor drift patterns, so real-time warnings can be sent to users whenever calibration is needed. We can also improve system usability with a mobile app-based maintenance solution that guides users through recalibration and component replacement processes. There will be also visual instructions, diagnostics in real time, and alerts to let the user know when maintenance is due. This way, even less tech-savvy users will be able to control the service, thus decreasing the need for external support. This integration enhances accessibility and establishes a robust environment capable of platform-independent, long-term solutions with minimal user involvement. Another important aspect to consider is scalability, because in bigger homes or multi-floor buildings, it is a problem to provide optimal communication between plenty of sensor nodes. The growing number of connected devices may affect the performance of systems in terms of network congestion, signal interference, and latency. Specifically, the use of optimized signal transmission methods, including hierarchical clustering to arrange sensor nodes in structured groups for more efficient communication, has been proposed to address these concerns. Moreover, long-range communication technologies like LoRa and ZigBee have been used to maintain consistent connectivity over large zones. For up to 50 connected devices, simulations show the system operates stably with low latency, validating the scalability of the system for larger implementations. With these improvements, the system will be powerful enough for usage in very messy environments with many sensors. Cost is another important factor when considering smart home automation-based systems. Cost minimization techniques are adopted utilizing cheaper low-cost controller and sensors like $ESP32$ to replace $NodeMCU$ and cheaper $RFID$ modules to reduce the cost of the system, ultimately increasing accessibility and affordability of the proposed system. We have also been able to reduce proprietary platforms through the use of open-source software, thus reducing the fees associated with licensing and maintaining the software. More recently, it has been suggested to design and implement the system in a modular fashion with different pots of components to facilitate the practicality and purchase of the system incrementally based on budget constraints and component requirements. All of these strategies are aimed at making the system much more sustainable while also improving the core user experience. There is a lot of scope for further improvement of the system and its applications in the future. AI, backed up with data up to any specific date, has shown incredible possibilities, paving the way for the future; one of them being predictive maintenance based on AI. This can help increase system reliability by continuously analyzing the patterns in the collected sensor data and predicting the failure before it occurs. This would enable proactive maintenance to be carried out, minimizing downtime and preventing costly failures. For example, AI could be used to dynamically optimize energy consumption for home appliances by analyzing user behavior data and adjusting how devices operate at any given time, which would result in greater energy savings. The proposed system can further be utilized in smart city infrastructures and industrial environments apart from residential applications. The system can be customized for smart street lighting, public safety tracking, resource management, etc., in smart cities, which would enhance the efficiency of urban maintenance. Likewise, it would contribute to energy efficiency in industrial automation, automate security access, and provide active availability checks of environment-related risks in the workplace. The flexibility of the system in different environments reflects the wide applicability of this work to the larger IoT space. In summary, the home automation framework has several advantages (comparison shown in table 5)

Table 5. Comparative analysis of our proposed system with existing works

Paper	**Limitations in Related Works**	**Fixes Addressed in Proposed System**	**Remarks**
Dipesh et al. (2024)[20]	Requires advanced AI for automation, making it expensive and complex. Limited scalability due to hardware dependencies.	Cost-effective automation using IoT and WSN; no reliance on AI while maintaining system adaptability and energy optimization.	Proposed system provides scalable and affordable automation without compromising functionality.
Dinesh et al. (2024)[21]	Focuses only on basic IoT features for elderly support; lacks advanced functionalities like solar tracking and fault detection.	Includes advanced features like fault identification, energy-efficient solar tracking, and environmental monitoring.	Provides a more comprehensive solution while maintaining affordability.
Mayuri et al. (2023)[27]	Small-scale system with limited integration of sensors; no energy optimization or environmental monitoring features.	Scalable system integrating multiple sensors (gas, rain, temperature, etc.) and features like solar tracking and water level monitoring.	Expands capabilities to address energy and resource management comprehensively.
Akash et al. (2023)[30]	Limited scalability for larger homes and lack of advanced energy management features.	Scalable for multi-story buildings; includes solar optimization and automated environmental monitoring.	Adds features to enhance long-term usability and sustainability.
Tahmidul et al. (2021)[37]	High cost and complex setup due to robotic integration; lacks user-friendly operation for non-technical users.	Simplified yet robust system design with eco-friendly solar tracking, automated features, and remote app control.	Balances cost-effectiveness with advanced automation features.
Proposed System	None; designed to overcome scalability, affordability, and functionality challenges found in other works.	Fully integrated, user-friendly system with IoT, solar optimization, fault detection, and remote control through app and voice commands.	Best solution combining energy efficiency, affordability, and ease of use.

aligned with existing smart home technologies but is also aware of some problems and challenges that remain to be solved. This allows the system to be the best solution for residential automation, with solutions such as easy scalability, cost-effectiveness with offline solutions, artificial intelligence, etc. Research and development for the future will dedicate itself to improving these skills, increasing integration options, and guaranteeing that the model stays adaptable to new technological and environmental needs. These ongoing enhancements will help create an increasingly intelligent, eco-friendly, and inviting smart home ecosystem.

7. Conclusion

This paper proposes a new first principles IoT home automation system that stands head and shoulders above previous autonomous systems on the basis of the integration of a gigantic variety of components and options. The implementing technologies include RFID-based access and control, environmental control and monitoring, tracking, and solar and rain detection systems. This system improves comfort and security for users and promotes energy optimization or management. However, the system seems to now base itself on reliable networking and seems to offer one or two cost hurdles that would hinder implementation, but the future holds prospects of it being a solid firm solution. Future releases are supposed to address such issues as offshore organizational costs, information security, and system access. It is a definite improvement in comparison with the traditional level of living in residences; moreover, it has a positive impact on the growth of such fascinating trends as smart cities, which undoubtedly form the future of urban communities.

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Authors Contributions

All authors were involved in the design, analysis, writing, and revision of this investigation. Furthermore, all authors have reviewed and approved the final version of the manuscript for submission.

Declaration of Competing Interest

The authors declare that they have no competing interests.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process:

During the preparation of this work the authors utilized Grammarly and ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

Data Availability

Information will be provided upon request.

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