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IoT-Based Home Automation System with Energy Monitoring and Optimization

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Abstract: Ordinary households are turning into intelligent, connected places because of the evolution of Internet of Things (IoT) technology. Still integrated energy monitoring, real-time safety features, and decision-making skills are absent in most of existing home automation systems.In this paper the design, development and implementation of an IoT-based home automation system that includes layered safety features, rule-based artificial intelligence (AI), and real-time energy monitoring into a single framework is presented.The DHT22 temperature-humidity sensor, PIR motion sensor, LDR light sensor, MQ-2 gas sensor, and four ACS712 current sensors for per-appliance energy monitoring are all interfaced with an ESP32 microcontroller. The Blynk IoT platform allows cloud connectivity and user interaction remotely.In the system three automation rules are used:fan regulation based on temperature, light regulation based on ambient light, and appliance control based on occupancy. When there is unoccupancy condition, all appliances turn off automatically, which results in significant energy savings. Safety measures include prevention of overcurrent by cutoff of each appliance relay if current consumption of appliance goes above 3.00 A and automatic turning on of exhaust fan for ventilation, also immediate shutdown of appliances after gas detection to avoid ignition risk. Quick reporting of critical events was done through blynk notifications and automated email alerts. The proposed system was evaluated between the period of January 2026 to April 2026 and the results showed constant automation accuracy, accurate current readings for all the four appliances, and reliable emergency response. So according to the results the proposed system offers a practical, scalable, and cost-effective solution for modern smart homes. So the presented system successfully addresses user convenience, operational safety, and energy efficiency.

Keywords: Internet of Things (IoT), home automation, sensors ESP32, energy monitoring, artificial intelligence (AI), smart home, Blynk

I. INTRODUCTION

Devices are easily connected through the internet for communication, remote access, and monitoring with the help of Internet of Things technology. Over time the Internet of Things (IoT) technology has made ordinary homes intelligent, connected and responsive residences. By connecting sensors, devices, and users, it provides automated control and remote monitoring.

Additionally, it makes use of real-time data to make decisions, which tends to improve convenience, energy efficiency, and overall safety [5], [25]. Modern home automation systems commonly use sensors, microcontrollers, and different cloud platforms to provide direct control of appliances using a computer or phone. Although it seems simple, it has completely changed how people interact with their houses [3], [26].

Most of systems simply provide basic automation, such as allowing users to turn appliances on or off remotely, so they typically do not show how much energy is actually being used by devices or how it could be reduced.So when we take into consideration the increasing concern about energy consumption this seems like a limitation. Some studies have explored the use of machine learning for prediction and optimization, but such approaches often increase complexity and computational burden, making them unsuitable for cost-effective or limited resources systems [4], [22], [23].

On the other hand, safety is not always given the same amount of attention. In many system designs, immediate detection of hazards—such as gas leaks or electrical faults—and rapid response mechanisms are either limited or absent. Quick response mechanisms and early detection of risks, including leakage of gas or electrical failures, are either not present or very limited in many system designs. According to earlier research, combining different safety layers in place of relying just on single mechanism improves system reliability in real-world situations [20], [27]. Real-world challenges also usually appear while the implementation. It is not as easy as it might appear to combine many types of devices, keep scalability, and keep the system user-friendly for users. While cloud platforms help by provide centralized access and real-time synchronization, effective processing towards the hardware level is still required for responsiveness [6], [17], [28].

This paper presents an Internet of Things (IoT)-based home automation system that tries to solve these problems by combining layered safety features, rule-based decision logic, and real-time energy monitoring in a single setup. To be able to enable context-aware actions, such as turning off appliances when not in use, changing lighting according to ambient levels, or turning on cooling as temperatures rise, the design makes use of an ESP32 along with sensors. the energy usage of each appliance is logged separately, and the system has safety features like prevention of overcurrent and gas detection. The users will able to monitor, control, and receive alerts because of cloud connectivity through the Blynk IoT platform, which makes the system functional as well as easily accessible for real-world use.

II. LITERATURE REVIEW

Research on IoT-based smart home automation has grown in many of directions, but not usually with the same depth or focus. In early works, automation and user convenience are given importance. For example, Leong et al. [1] explored AI-driven automation and observed improvements in efficiency and personalization; at the same time, privacy and interoperability challenges started to arise. In a more hardware oriented way, Ghoul et al. [2] developed an Arduino-based system that includes gas and environmental sensors with mobile application for real-time monitoring. While Francis et al. [4] went one step further by using ensemble machine learning to optimize electricity use, Bangera et al. [3] focused on wireless control and security. These studies point that improvements are taking place , but they also point out the possibility of increase in system complexity.

Architectural design has also received more attention over time. Stolojescu-Crisan et al. [5] proposed an API-based platform to simplify device integration. Though the idea is practical, but details about its implementation can differ. Ishaq et al. [6] proposed a cloud based framework which was designed to further improve remote access and data security, while Tsankov et al. [7] evaluated a hybrid architecture that could function even in the absence of continuous internet connectivity.

This offline functionality is useful but it raises issues about reliability and synchronization. To give automation, security, and monitoring in one system, Mussa et al. [8] integrated IoT and wireless sensor networks. Similarly, Condon et al. [9] used real-time data handling for energy management while Mohammedi et al. [10] used home assistant-based setup for interoperability.

Energy efficiency continues to be the common theme, even though the methods and approaches change. Das et al. [11] suggested considerable reduction in energy consumption using an ESP32-based system design, while Adetunla et al. [12] focused on system accuracy in addition to efficiency. Eliş et al. [13] gave preference to Low-cost, open-source system implementation, which might be more helpful in practical implementations. Both Kabir et al. [14] and Niranjana et al. [15] made use of sensor based control, with the latter focusing on faster response times through effective sensor association. Chavan et al. [16] explored electrical control and gave primary focus on remote operation and energy savings, but scalability is not always clearly addressed.

The studies usually include cloud integration, which is often used as a way to solve coordination issues. Balamanikandan et al. [17] used Firebase with NodeMCU in order to provide real-time synchronization and Gurumurthy et al. [18] combined cloud platforms with mobile interfaces to improve usability. While these methods make control easier, they may cause latency or problems related to dependency, usually when the network is unstable.

Security and control mechanisms are widely discussed and are handled with different levels of depth. Manonmani et al. [19] introduced feedback-based monitoring, improving responsiveness to certain degree. In order to prevent unauthorized access Solangi et al. [20] focused on authentication and Arunadevi et al. [21] included secure communication and RFID-based control. Mishra et al. [22] explored machine learning for predictive energy optimization, while Ray et al. [23] focused on occupancy-based automation to reduce unnecessary usage of energy. Each method addresses part of the problem, but all aspects are rarely addressed together.

Recent work questions user experience and system dependencies. Lawanya Shri et al. [24] proposed a architecture which is fully based on local server, so that the dependency on cloud will reduce. This approach could limit scalability but it improves privacy. Next generation systems including adaptive learning as well as real-time responsiveness were discussed by Kumar et al. [25], but the details of their actual implementation were not clear. Khan et al. [26] used API-based Android control to offer flexibility and Gayatri et al. [27] improved the functionality by adding waste management and safety measures including gas detection. Srinivasrao et al. [28] focused on interface design and usability and suggested that adoption needs more than simply techni cal performance. Overall the studies showed a gradual transition from simple remotely operated and controlled systems to more advanced, intelligent, and interconnected systems. But certain issues are still there. The issues like scalability, security, and interoperability still remain unaddressed, and in many cases improvements in one area seem to come with compromises in another.

III. MATERIALS AND METHODS

A. *System Overview*

The developed system can be considered as layered IoT-based home automation system Instead of being simply a basic control system setup. The proposed system combines cloud interaction, energy monitoring, rule based decision logic, and environmental sensing into one functional architecture. The ESP32, which is set up in the center, it uses Wi-Fi to connect and communicate to the Blynk IoT platform. Instead of managing each function separately the architecture is separated into interacting blocks: sensor input, embedded processing, relay-based switching, feedback via current sensing, and appliance control.In the feedback loop, the energy data is not only observed but it is fed back into system decisions. This makes the system less fixed than other normal implementations

B. *Hardware Components*

Both computation and communication are managed by the ESP32 microcontroller. The ESP32 becomes good choice because of its built in WI-FI and ADC channels, but there are limitations such as limited precision under noisy environments. Every 500 ms the microcontroller goes through sensing, decision-making, safety checks, and cloud updates , which is quick enough for responsiveness but is not strictly real-time. Through GPIO 27, the DHT22 sends temperature and humidity data. An LDR on GPIO 36 is used to determine the light intensity; day and night can be identified by an experimentally chosen ADC threshold (1000/4096). Even though it is useful, this threshold can vary a little depending on the surroundings. A PIR motion sensor connected to GPIO 14 is used for occupancy detection. Although its binary output makes logic less complicated, but it is not able to record motion intensity or count. The MQ-2 gas sensor connected GPIO 26 is used for gas detecting, it reacts to gases like methane and LPG. It immediately activates a safety response when it is triggered.Four ACS712 sensor modules are used to perform energy monitoring. These use a peak-to-peak sampling technique over 100 ms to measure each appliance's current, from which an RMS-equivalent value is obtained. The system switches off the corresponding relay if current on any channel goes above 3.00 A. This method helps to provide safety, but it may occasionally react to minor spikes. In order to perform relay control a ULN2803G driver IC connects the logic levels of the ESP32 with 5V relays. These four SPDT relays manage the switching of appliances that is 12V loads.

C. *System Architecture*

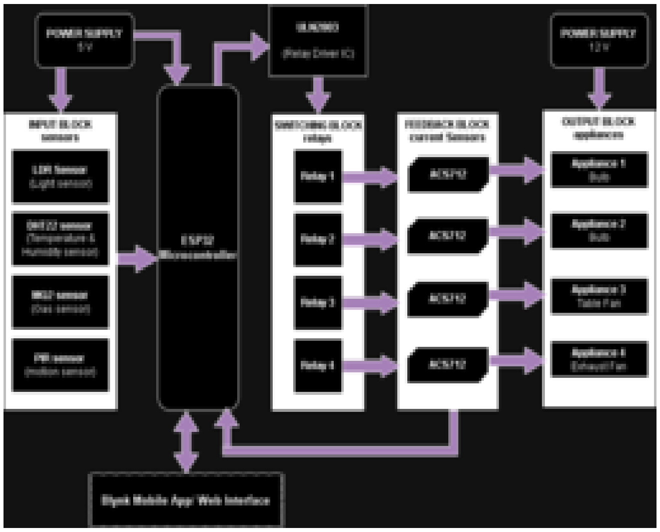


Figure 1: The functional block diagram of the complete system.

As shown in Figure 1 the system architecture instead of using separate stages, has a continuous data flow. The ESP32 gets sensor inputs directly and uses them for processing, safety evaluation, and rule execution.

The switching block which is of the driver IC and relays acts on these decisions, while the current sensors complete the loop by giving real-time electrical data. Monitoring and intervention are made possible by cloud interaction through Blynk.

D. Circuit Design and Connections

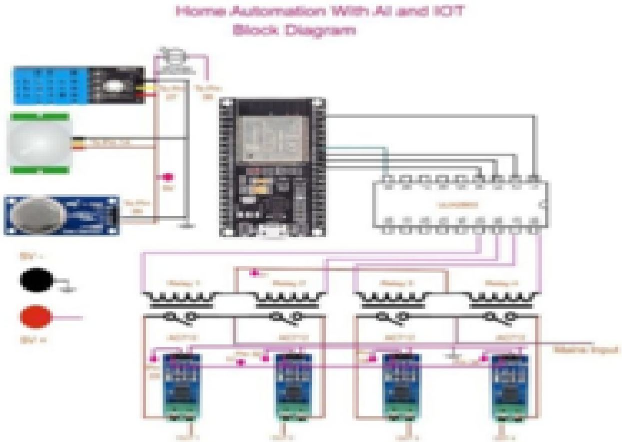


Figure 2: The complete wiring and connection diagram.

The system has quite neat mapping between sensors and GPIO pins from a wiring point of view as shown in Figure 2. The DHT22 sensor is connected to GPIO 27, LDR to GPIO 36, PIR to GPIO 14, and MQ-2 to GPIO 26 and they all share a 5V power supply. GPIO pins 5, 23, 19, and 18 are where the relay control signals originate and they go through the ULN2803G before reaching at relay coils. A series path which enables simultaneous control and measurement is made by connecting each appliance to its corresponding relay and ACS712 sensor.

E. Physical Hardware Implementation

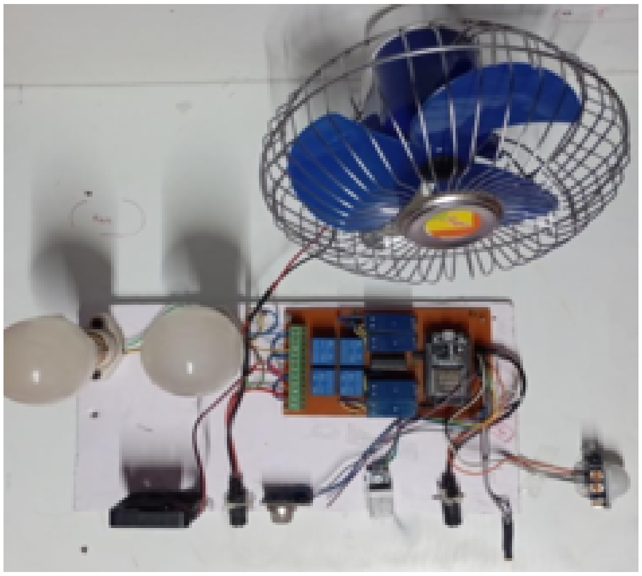


Figure 3: The assembled prototype of the system

Figure 3 shows the assembled prototype in which the structure is both compact and useful. A single PCB is made to include the ESP32 microcontroller, relay modules, driver IC, and current sensors. To make sure accessibility is achieved, peripherals like the lights, fans, and sensing modules are placed around the board. The color coding allows a visual distinction of wiring (5V vs. 12V), which, in spite of its simplicity, helps re ducewiring errors which can cause during testing and maintenance.

F. Software and Firmware Design

Thesystem firmware includes libraries like WiFi.h, BlynkSimpleEsp32.h and DHT.h. A timer based structure is used rather than depending on blocking delays. The system executes sensor reading, safety verification, execution of AI rules, and cloud synchronization every 500 milliseconds.

Automation logic is purposefully placed after safety checks. Because of this hazardous conditions, such as gas detection or overcurrent, will be given priority before all other operations.

Blynk virtual pins (V0–V4) are used to handle user interaction, which enable manual control and mode switching without affecting the main loop.

G. AI-Based Automation Logic

Because the automation layer is rule-based rather than predictive, so computation has become simple.When Auto Mode is turned on, three rules operate constantly.

If no occupancy is detected within 500 milliseconds, the first rule turns off all the appliances. This short timeout may seem impractical in real-world situations, even though it is a good way to save energy The second rule controls lighting based on occupancy and ambient conditions to keep a balance between efficiency and visibility. The third rule makes use of temperature thresholds to switch the fan and only starts it when both a high temperature and human presence are detected. These rules never take precedence over the safety rules. While it prevents conflicts, this design approach kind of limits flexibility.

H. Cloud Platform and Notification System

The Blynk IoT platform is structured around 15 virtual pins for data transfer and control and it also acts as a cloud interface. The system uses Blynk.logEvent ("gas_leakage") to trigger an event that sends a notification and an email when it detects a gas leak. In situations where one channel may be failed, there this dual alert system increases reliability. As it depends on steady network connectivity, which in some cases could influence response time.

IV. RESULT AND DISCUSSION

A. Overview of System Performance

The system prototype was evaluated by using four factors: environmental sensing reliability, energy monitoring accuracy, safety response (gas leakage and overcurrent), and AI based automation.

From January to April 2026, the data was regularly recorded using the Blynk IoT platform.

During this time period the system typically responded in real time and the automation decisions were closely corresponding to the sensor inputs. Cloud synchronization seemed reliable throughout, but like other IoT systems, this reliability will continue to depend on network conditions in bigger implementations.

B. AI-Based Automation — Auto Mode Results

1) Low Ambient Light (Night Condition),Human Presence detected:

Figure 1: The Blynk dashboard where Auto Mode is enabled, PIR sensor detects human presence, and the LDR detects darkness.

Figure 1 shows a scenario where the Auto Mode is turned on, the occupancy and low ambient light is detected. The human presence in dark surroundings is indicated by the system logging humanState = 1 and lightState = 0. The temperature and humidity values (37.9°C and 37.4%) are higher than the temperature threshold.

In this situation, two rules execute simultaneously over the 500 ms cycle: the fan starts because of the high temperature and presence, also the lighting is turned on because of the darkness and presence. Current readings across the channels show that the condition is working (both lights ON, fan ON, exhaust OFF). The measured current readings show that relay switching allows for actual load operation instead of staying at a software level.

2) Human Detected, High Ambient Light (Day Condition)

In Figure 2 somewhat different situation is shown, where presence is still detected but ambient light is enough (lightState = 1). So even the temperatures (~38°C) remains same, the light turns off and the fan keeps running. The fan rule only responds to temperature and occupancy, while the lighting rule only responds to ambient light.

When we compare the current channels it shows the independence between the rules: Channel 3 indicates active consumption, while Channels 1 and 2 stay at zero. It shows that the rule execution does not overlap, which reduces the accidental interference between conditions.

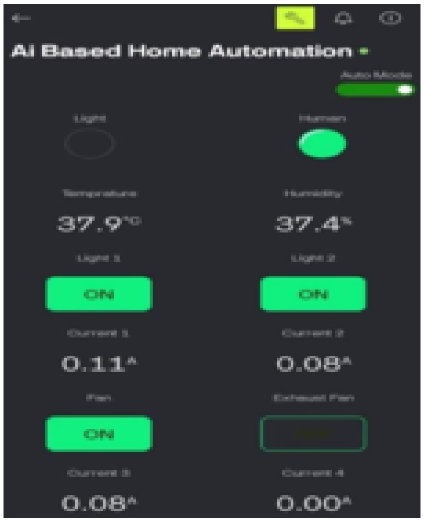


Figure 2: The Blynk dashboard when Auto Mode is enabled, human presence is detected, but the LDR sensor detects enough ambient light.

3) No Human Detected

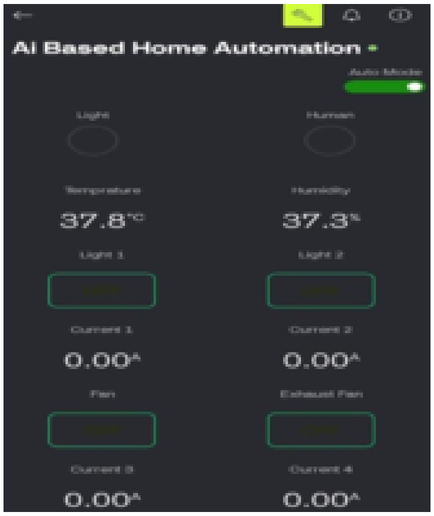


Figure 3: Blynk dashboard with Auto Mode enabled and no occupancy detected.

The proposed system in the absence of occupancy is shown in the Figure 3. Both humanState and lightState are zero which shows that the room or surroundings is dark and empty. After the set timeout period all the appliances are switched off regardless the high temperature (~37.8°C). Rule priority is highlighted by this behavior. Temperature based rule takes over with occupancy-based shut down which helps in reducing wasteful energy usage. When compared to the earlier scenario the effect seems clearer in which just occupancy changes, identical environmental factors result in completely different system states.

C. Manual Mode Operation


AI Based Home Automation

Auto Mode

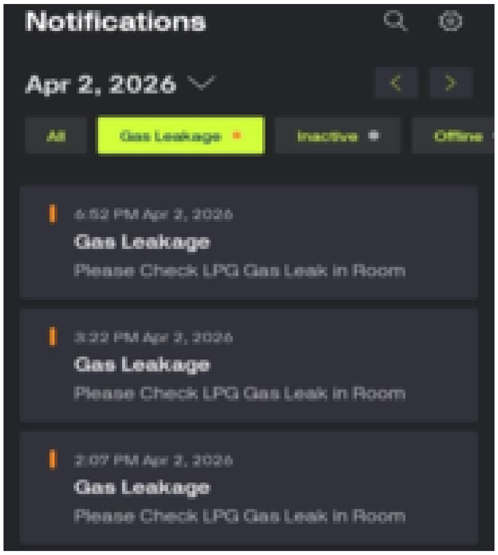
Temprature 37.8°C
Humidity 36.8%
Current 1 0.00A
Current 2 0.00A
Current 3 0.00A
Current 4 0.00A

Figure 4: Blynk dashboard when the system operating while Auto Mode is off

The behavior of the system when automation is turned off can be seen in Figure 4. In this scenario appliance activation is totally dependent on human input. This is confirmed by current readings of all the appliances. Even the temperature reading is high, the automated response is absent which shows that the execution of rules is completely skipped in manual mode. Even if it is simple, this flexibility becomes important in real-world situations.

D. Gas Leakage Detection and Emergency Response

1) In-App Notifications


Notifications

Apr 2, 2026

6:52 PM Apr 2, 2026
Gas Leakage
Please Check LPG Gas Leak in Room

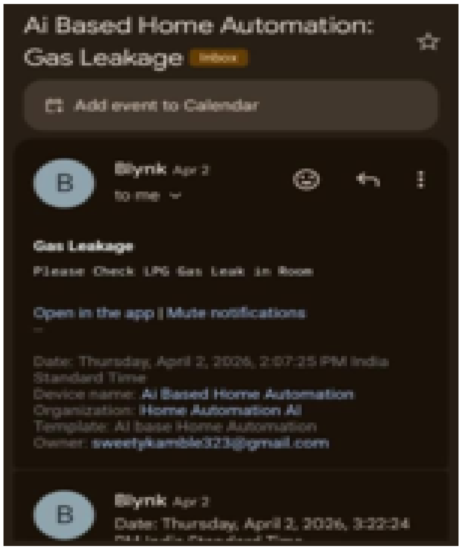
3:22 PM Apr 2, 2026
Gas Leakage
Please Check LPG Gas Leak in Room

2:07 PM Apr 2, 2026
Gas Leakage
Please Check LPG Gas Leak in Room

Figure 5: The Blynk Notifications panel showing logged gas leakage events on April 2, 2026

Gas leakage events that took place three times on April 2, 2026, are showed in the Figure 5. Every incident has the same alert message and timestamp, showing that logging and detection was continuous. Within the same processing cycle, the system responds when the MQ-2 gas sensor is activated by turning off unnecessary loads and turning on the exhaust fan. A cloud event is generated simultaneously.The repetition of accurately recorded events show reliability but it would still be useful to observe the behavior under continuous or noisy gas conditions.

2) Email Alerts



Ai Based Home Automation: Gas Leakage

Blynk Apr 2
to me

Gas Leakage
Please Check LPG Gas Leak in Room

Open in the app | Mute notifications
--

Date: Thursday, April 2, 2026, 2:07:25 PM India Standard Time
Device name: Ai Based Home Automation
Organization: Home Automation AI
Template: AI base Home Automation
Owner: sweetykamble323@gmail.com

Blynk Apr 2
Date: Thursday, April 2, 2026, 3:22:24

Figure 6: The automated email alert received in the user's inbox following a gas detection event.

The corresponding email notifications are shown in Figure 6. The metadata like the message content, device identity, and timestamp are present in every alert. Notifications are not suppressed or mixed even if there are many emails for different events. Redundancy is added with the help of this dual channel alert mechanism, which uses email and push notifications. If one communication channel fails due to some issue this redundancy can be important in real world implementation.

E. Energy Monitoring — Current Sensor Analysis

1) Channel 1 — Light 1

Figure 7 Three-month current readings recorded for Appliance 1 from January 7 to April 7, 2026.

Continuous current readings for appliance 1 all throughout a three-month time period can be seen in Figure 7. The peaks shown, correspond to situations in which both darkness (low ambient light) and occupancy (human presence) are present. Instead of continuous operation, conditional based triggering is shown in the discontinuous pattern. Most importantly, every value stays below the 3.00 A threshold, which shows continuous operation without activating safety mechanisms.

2) Channel 2 — Light 2

Figure 8: Three month current readings history for appliance 2.

The graph pattern in Figure 8 is quite similar to that of the appliance 1. Peak values are a bit lower (~0.09 A), and small variations may be caused by calibration or hardware errors. The idea that both lighting outputs are controlled similarly under the same conditions can be proven by the close relationship between appliance 1 and 2.

3) Channel 3 — Fan

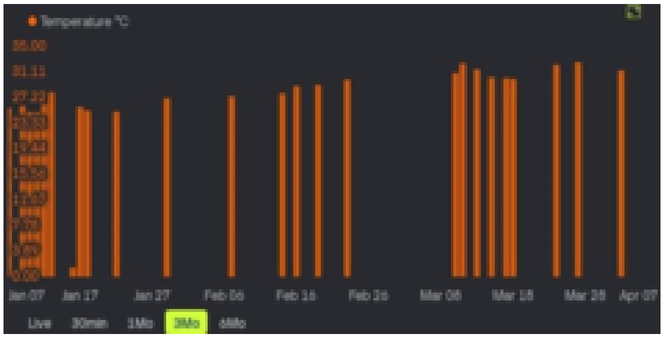


Figure 9: Three month current readings history for Appliance 3.

Figure 9 shows a more continuous activity profile. Unlike lighting, fan operation depends only on temperature and occupancy, not ambient light.

One interesting observation appears around late January—a spike in fan activity without corresponding lighting activity. This suggests a daytime scenario where temperature conditions were met, but lighting rules were inactive.

Such distinctions reinforce the independence of rule execution.

4) Channel 4 — Exhaust Fan

Figure 10 covers the three-month current history for Channel 4.

Low activity can be seen in Figure 10, with a few noticeable peaks in early April. These peaks correspond to gas leakage events that have been recorded, which shows that the exhaust fan works mainly as a safety actuator.

F. Environmental Monitoring

1) Temperature

Figure 11: The three-month temperature log from the DHT22 sensor, from January 7 to April 7, 2026.

The temperature increases gradually from January (~24°C) to April (>31°C), as shown in the figure 11. this trend is consistent variation in the seasons. Midway in January, there is a near-zero reading which likely shows a temporary sensor or connection problem instead of an environmental change. Other than this, readings don't change much. The temperature-based rule is applicable throughout the system testing period because temperatures continue to go above the threshold for fan activation.

2) Humidity

Figure 12: Three-month humidity readings graph from the DHT22 sensor.

The humidity levels which are shown in Figure 12 are generally between 43% and 65%. Variations do not seem to be sudden and are gradual which shows stable functioning of the DHT22 sensor. Temporary system interruption can be confirmed by the presence of the same a pattern seen in temperature data. The reliable data shows a potential for future advancements, like moisture based ventilation management, even though humidity values are not currently used for automation purpose in the system.

G. Discussion

In all examined situations, the automation logic appears to work properly. Unnecessary energy consumption is prevented using rule prioritizing, mainly the priority of occupancy based shutdown. Problems between temperature control and light are also avoided using independent rule execution. Each recorded gas leakage event has a similar level of safety performance. Both immediate action and user awareness are offered by combining of cloud-based alerts and instant hardware response. An extra level of insight is given by energy monitoring. It provides verifiable proof of system performance over time, rather than the use of vague measurements. Channel differences are not random, rather they are directly relate to the ways in which each rule works.

So altogether the results show that the system functions reliably in controlled conditions. It would be worthwhile to explore whether this level of consistency remains in more variable real-life situations.

V. CONCLUSION

This paper presented the design and implementation of an Internet of Things (IoT) based home automation system that includes real-time energy monitoring, rule-based decision logic, and integrated safety features into a single structure. This ESP32 based system uses the Blynk IoT platform for cloud connectivity, embedded control and environmental sensing. The system seems to be more advanced than many basic automation systems because the components function collectively rather than as independent components. Based on the observations made throughout the three month evaluation time period it is observed that he automation seems to function effectively under different situations. The rule-based AI manages switching of the appliances based on occupancy condition, switches light in response to surrounding light conditions and manages fan operation based on temperature. By responding to only its own events, each rule helps to an overall decrease in energy consumption. Additionally, the system prevents unnecessary intervention, which improves user comfort. The Energy monitoring with the help of ACS712 sensors provide appliance-level data rather than average estimations. Thus, it is possible to observe consumption patterns over time and make a direct correlation with automation behavior. Along with the confirmation operation, the data collected gives confirmation of how and when energy savings take happen. Safety performance is another area where the proposed system shows consistent behavior. When the MQ-2 gas sensor detects gas leakage, the unneeded loads are immediately turned off and the exhaust fan gets switched on for ventilation. While the overcurrent protection mechanism further ensures that each appliance functions within defined limits. Redundancy is implemented by notifications given over the cloud platform using email and in-app alerts, which can reduce the probability of missing warnings. Thus, the system shows features that suggest applicability in real-world scenarios. It handles energy consumption, safety, and usability in an appropriate way while being cost-effective and scalable. However, an extension is still possible. Predictive models, particularly using lightweight machine learning, along with supporting more devices and environmental factors, could be explored in the future studies. Such improvements could improve adaptability but they would also need to be balanced against increasing system complexity.

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