Design and Implementation of a Bluetooth-Based Smart Home Automation System

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Abstract- This study presents the design and implementation of a cost-effective smart home automation system based on Arduino Nano and Bluetooth technology. The system integrates multiple household appliances into a unified control platform accessible via smartphone. The hardware configuration includes an Arduino Nano microcontroller, HC-05 Bluetooth module, relay modules, and a regulated power supply, while the software framework was developed using the Arduino IDE. Both simulation and practical implementation demonstrated reliable appliance switching—such as light bulbs and fans—within the effective Bluetooth range, with stable voltage regulation and real-time responsiveness. The proposed system enhances convenience, safety, and energy efficiency, offering benefits for the elderly and physically challenged. However, limitations were observed, including the restricted communication range of Bluetooth and the absence of cloud connectivity for remote access. Future work will address these challenges by incorporating multi-protocol interoperability, cloud integration, and advanced security features, thereby expanding the system's scalability and reliability for broader smart home applications.

Keywords: Smart home automation, Arduino, Bluetooth control, Wireless control, home energy management and IoT.

I. INTRODUCTION

Technological advances have transformed household management, enabling the integration of wireless communication protocols for efficient control of appliances. Smart homes enhance convenience, energy conservation, and security, offering solutions to challenges such as electrical accidents and power wastage. In Nigeria, where energy crises and safety concerns persist, affordable automation systems can mitigate risks of electrocution, prevent appliance misuse, and improve quality of life.

Recent research on residential automation spans multiple wireless technologies. Wi-Fi, ZigBee, Bluetooth Classic/LE, and hybrid Internet of Things (IoT) stacks each with trade-offs in cost, range, latency, energy use, and integration complexity. Foundational studies using Internet/Wi-Fi backbones demonstrated flexible remote control but at the expense of higher energy consumption and configuration complexity (Alkar & Buhur, 2005; Kumar et al., 2020). ZigBee and other IEEE 802.15.4 options improved scalability and mesh coverage for sensor dense homes, especially for energy management, yet introduced gateway costs and protocol overheads (Han et al., 2010; Sivapriyan et al., 2020). Broader surveys consistently surface cross-cutting challenges security and privacy, interoperability, and usability alongside opportunities for context awareness and aging in place support (Alam et al., 2018; Zhang et al., 2019; Diaz et al., 2023).

The advent of the IoT has transformed how data is collected, transmitted, and applied across various sectors. IoT is a network of interconnected physical devices, or "things", embedded with sensors, software, and communication technologies to collect and exchange data over the Internet (Bulipe et al., 2016; Akpakwu et al., 2018). IoT involves low-power devices that communicate with one another via the Internet. The IoT has captivated the research community, aiming to connect wearables, sensors, smart appliances, washing machines, tablets, smartphones, smart transportation systems, and other entities to a unified interface for intercommunication (Palatella et al., 2016; Borgia 2014; Al-Fuqaha et al., 2015).

Within this landscape, Bluetooth has matured from short range device pairing to a credible smart home control fabric. Classic Bluetooth SPP (e.g., HC-05/HC-06) remains attractive for ultra-low cost, smartphone-centric switching, particularly in single room or apartment deployments (Sriskanthan et al., 2002; Sharma et al., 2017). Bluetooth Low Energy (BLE) extends battery life and supports larger device counts and improved reliability, while newer Bluetooth 5.x features—LE 2M PHY, Coded PHY, Direction Finding, and Isochronous Channels expand range, add positioning, and enable synchronized multi node control (Bluetooth SIG, 2023; Collotta & Pau, 2015). Comparative reports still note Bluetooth's range and network size limits relative to mesh first protocols; however, its ubiquitous smartphone support, minimal commissioning friction, and low bill of materials make it compelling for budget sensitive deployments (Kumar et al., 2020; Alam et al., 2018).

Despite these advances, gaps persist for contexts like Nigeria and similar emerging markets: (i) affordability and maintainability under intermittent power supply; (ii) safety to reduce electrocution incidents through galvanic isolation and low voltage control paths; (iii) offline robustness where cloud connectivity is unreliable; and (iv) interoperability to avoid vendor lock in while preserving simple on boarding (Alam et al., 2018; Zhang et al., 2019). Prior Bluetooth prototypes often emphasize functionality but underreport safety engineering (relay isolation/clearances), regulated power design (e.g., thermal analysis of linear regulators), and usability for elderly/disabled users (Sriskanthan et al., 2002; Sharma et al., 2017).

This study develops a Bluetooth based home automation system that allows users to control appliances such as lights and fans via smartphone. Unlike Wi-Fi or ZigBee systems, Bluetooth provides low-cost implementation without Internet dependency, making it suitable for localized environments. Table 1 presents the characteristics of wireless automation technologies.

Table 1: Characteristics of Wireless Automation Technologies.

Protocol	Bluetooth	Wi-Fi	ZigBee
Frequency	2.4GHz	2.4GHz, 5GHz	868MHz, 915MHz, 2.4GHz
Modulation	FHSS	QPSK, COFDM, QAM	BPSK, O-QPSK
Error Control	CRC (16-bit)	CRC (32-bit)	CRC (16-bit)
Range	10m	100m	10m - 100m
Network Size	8	2007	64000
Power Consumption	Medium	High	Very Low

In Nigeria, persistent power crises, rising energy costs, and domestic accidents such as electrocution necessitate the design of safe and energy efficient automation solutions. Conventional wired systems are costly, rigid, and prone to electrical hazards, while existing smart home solutions often remain expensive and inaccessible to the average household. There is therefore a pressing need for a low cost, Bluetooth based system that integrates multiple appliances into a single platform for enhanced safety, convenience, and efficiency. Thus, the proposed Bluetooth based smart home automation system adapts the Arduino Nano for the control of domestic appliances. To summarize, the main objectives/contributions of the proposed work are the following:

i. We have developed a secure and reliable wireless system to reduce electrical accidents.
ii. Ensure seamless connectivity between smartphones and appliances through Bluetooth.
iii. Enable interoperability among multiple household devices via a centralized microcontroller and provide a user-friendly interface for efficient appliance management.

The rest of this paper is structured as follows: In Section II presents the related literature review and followed by a discussion about methodology and system design in Section III. Section IV provides the results and discussion. Section V concludes the paper and presents possible recommendations for future work and implementation.

II. LITERATURE REVIEW

Home automation systems are rooted in the broader concept of cyber physical systems (CPS), which integrate computational algorithms, communication networks, and physical processes to achieve intelligent control (Lee, 2008). CPS theory emphasizes real time monitoring, feedback loops, and seamless integration between digital commands and physical responses, which form the bedrock of smart home technologies (Rajkumar et al., 2010). In this study, the theoretical foundation rests on CPS as it enables the synchronization of hardware components such as relays, sensors, and actuators with software driven communication protocols to optimize household appliance management. By leveraging this framework, smart home systems ensure not only efficiency but also scalability, flexibility, and enhanced energy management (Gubbi et al., 2013).

Within this CPS context, Bluetooth communication technology plays a pivotal role. Operating in the 2.4 GHz ISM band, Bluetooth enables low power, short range, and secure data exchange, making it particularly suitable for residential environments where appliances are confined within a limited space. Bluetooth's master slave architecture facilitates effective device pairing and command execution, which aligns with CPS's objective of real-time responsiveness and reliability. Furthermore, literature suggests that Bluetooth based systems are preferred for cost effective automation in developing countries due to their low energy consumption and affordability compared to Wi-Fi or ZigBee alternatives (Al-Ali & Al-Rousan, 2004; Islam et al., 2017).

Additionally, the theoretical framework draws upon the IoT paradigm, which extends CPS concepts by embedding connectivity into everyday devices, allowing for remote monitoring and control (Atzori et al., 2010). IoT driven automation emphasizes interoperability, scalability, and user centered control interfaces, thereby enhancing the scope of smart home applications. However, unlike cloud dependent IoT systems, Bluetooth based CPS offers a decentralized, offline alternative that is less vulnerable to connectivity issues and external cyber threats (Sadeque et al., 2019). This dual grounding in CPS and IoT frameworks highlights the balance between local control and broader system scalability, providing a robust theoretical justification for the present study on Bluetooth controlled smart home automation.

Kumar (2016) developed a Wi-Fi based smart home automation system that enabled remote appliance monitoring and control via smartphones. The study demonstrated the effectiveness of Wi-Fi in providing long range connectivity and integration with cloud platforms. However, Wi-Fi solutions were found to require higher infrastructure costs, stable internet connectivity, and advanced technical setup, which makes them unsuitable for widespread adoption in low- and middle-income households. These limitations highlight the need for simpler, more cost-effective alternatives, especially in developing countries where affordability and energy efficiency are critical concerns (Mishra & Sharma, 2018).

In another study, Sharma et al. (2017) introduced Bluetooth based smart locks, emphasizing the security and ease of use provided by Bluetooth's pairing mechanism. Their design highlighted how Bluetooth could serve as a reliable communication protocol for short range applications within household environments. Nonetheless, the study also noted that Bluetooth's limited range (typically 10 meters for Class 2 devices) could restrict usability in larger homes or buildings. Similarly, Sivapriyan and Manigandan (2020) designed a ZigBee based automation framework that demonstrated improved scalability and multi device integration compared to Bluetooth. However, their system required higher technical expertise and more expensive hardware, which reduced its suitability for cost sensitive users. These studies collectively underscore the tradeoffs between cost, scalability, and ease of use across different wireless communication protocols.

Other researchers have also explored hybrid and emerging approaches. Al-Ali and Al-Rousan (2004) presented a Java based smart home system integrating microcontrollers with the internet, which provided flexibility but demanded higher programming knowledge and infrastructure. Islam et al. (2017) reviewed home energy management systems within smart grids, noting that while Wi-Fi and ZigBee dominate energy focused applications, Bluetooth remains more affordable and suitable for smaller scale domestic settings. More recently, Sadeque et al. (2019) proposed a low-cost Bluetooth controlled automation system tailored for developing nations, stressing that offline, localized systems can mitigate both connectivity challenges and cybersecurity risks. Similarly, Gunge and Yalagi (2016) highlighted how integrating Bluetooth with Android based applications ensures broader accessibility for users without advanced technical skills.

Taken together, the reviewed literature demonstrates that while Wi-Fi and ZigBee technologies offer greater scalability and integration with advanced smart grid infrastructures, their adoption is hindered by cost, complexity, and dependency on continuous internet access. Bluetooth, on the other hand, offers an affordable, energy efficient, and user-friendly alternative that is especially suitable for localized home automation in resource constrained environments. This provides a strong justification for the present study, which seeks to design and analyze a Bluetooth based smart home system that balances affordability, simplicity, and functionality in meeting domestic automation needs.

Although many studies validate Bluetooth as a practical control medium for home automation, there is limited work that explicitly addresses the combined constraints of affordability, intermittent power, and maintainability typical of many Nigerian households. Large scale Wi-Fi and cloud centric solutions deliver rich features but require continuous internet access and higher capital/operational expenditure conditions that are often infeasible in low-income or off-grid settings (Al-Ali & Al-Rousan, 2004; Kumar et al., 2020). Regionally focused studies recommend “offline first” architectures and minimal BOM (bill-of-materials) designs to improve adoption in resource constrained contexts (Sadeque et al., 2019; Diaz et al., 2023). Safety and engineering rigor remain underreported in many prototype reports. While Arduino + HC-05 hobby projects demonstrate basic functionality and rapid time to prototype, they often omit discussion of essential safety engineering: galvanic isolation between mains and control electronics, thermal dissipation of linear regulators under battery and mains charging scenarios, relay contact ratings versus inrush currents, and EMC/EMI mitigation in the ISM band (Sriskanthan et al., 2002; Sharma et al., 2017). Standard-oriented reviews and energy management literature emphasize that reliable field deployments must document clearances, creepage distances, certified relay modules, and power supply heat budgeting areas sparsely covered in existing Bluetooth prototypes (Han et al., 2010; Collotta & Pau, 2015). This omission creates a translational gap between laboratory demonstrations and safe, certifiable products appropriate for domestic installation.

Finally, usability, interoperability and upgraded pathways are incompletely addressed. Human factor and aging in place research show that successful adoption depends on simple onboarding, accessible interfaces for elderly/disabled users, and the ability to integrate with other devices or migrate to BLE/Wi-Fi gateways over time (Zhang et al., 2019; Graafmans et al., 2007). Many Bluetooth designs prioritize functionality over user studies and long-term maintainability; few document firmware update mechanisms, authenticated pairing procedures, or a clear path from classic SPP modules to BLE 5.x or mesh/gateway architectures that provide larger coverage and cloud services when available (Bluetooth SIG, 2023; Collotta & Pau, 2015). The present study therefore targets these combined gaps by developing a low-cost, galvanically isolated Arduino/HC-05 relay system with regulated power budgeting, simple onboarding for non-technical users, documented safety margins, and an explicit migration plan to BLE and gatewayed IoT for future scalability.

III. METHODOLOGY AND SYSTEM DESIGN

This section presents the various hardware components and software implementation for the proposed Home Automation System.

System Architecture:

The proposed system architecture integrates a smartphone interface, Bluetooth module, Arduino Nano microcontroller, relay driver circuit, and household electrical loads, forming a cost effective and reliable automation framework. The smartphone acts as the command interface, transmitting control signals via Bluetooth to the HC-05 module, which ensures low power, short range, and secure wireless communication suitable for domestic environments. These signals are processed by the Arduino Nano, chosen for its affordability, compact design, and compatibility with open-source libraries, making it ideal for rapid prototyping and deployment in resource constrained settings. The processed commands are routed to a relay driver circuit, which isolates low voltage control signals from high voltage loads, ensuring safe switching of appliances such as fans, lighting, and televisions. Several studies emphasize that Bluetooth based automation provides a more affordable alternative to Wi-Fi and ZigBee, especially in developing regions, due to lower infrastructure and energy demands. Moreover, the modularity of this architecture allows for scalability, enabling future integration with IoT gateways or BLE mesh networks for enhanced interoperability and remote control. Thus, the system balances simplicity, safety, and flexibility, making it highly adaptable for real-world smart home applications. Figure 1 shows the block diagram for the Home Automation System.

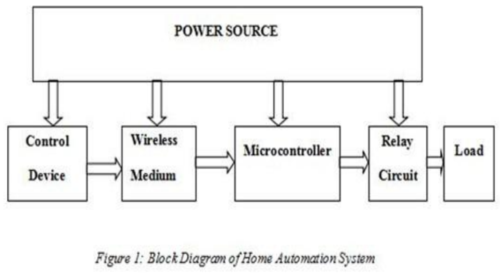

Figure 1: Block Diagram for the Home Automation System.

HARDWARE DESIGN:

Arduino Nano:

The Arduino Nano is a compact ATmega328P based microcontroller board operating at 16 MHz, supporting UART, SPI, and I²C communication protocols, making it suitable for embedded control applications in constrained environments. Its small form factor, low cost, and compatibility with open-source libraries make it a preferred choice for rapid prototyping in smart home automation. Prior studies emphasize that Arduino platforms lower entry barriers for automation projects by providing modularity and community driven support, which are critical in developing regions where technical expertise is limited. Figure 2 is a representation of the Arduino Nano V3 – and Pin description used for the project work.

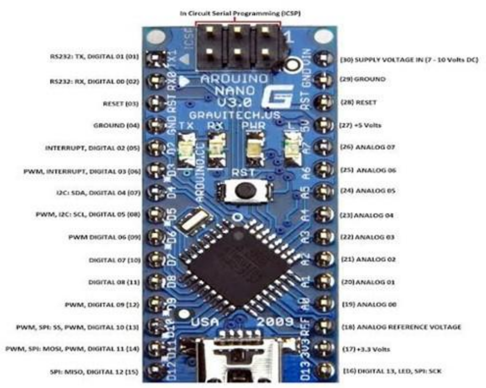

Figure 2: Arduino Nano V3 – Pin Description.

HC-05 Bluetooth Module:

The HC-05 Bluetooth module is a Class-2 device designed for wireless serial communication with a typical range of 10–15 meters in indoor environments, operating within the 2.4 GHz ISM band. It employs a master-slave architecture that simplifies pairing with smartphones for seamless appliance control. Researchers highlight their affordability, energy efficiency, and compatibility with microcontrollers, making it a widely used communication component in short-range home automation prototypes. Compared to Wi-Fi or ZigBee, HC-05 provides a low cost, offline first solution that suits households in regions with unstable internet access. Figure 3 shows the Bluetooth Module used for configuration of the proposed Home Automation System.

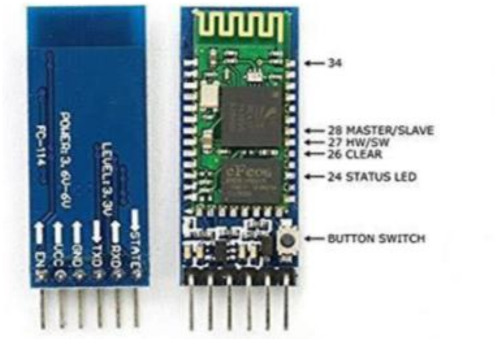

Figure 3: HC-05 FC-114 Bluetooth Module.

Relay Module:

The relay module acts as an electromechanical switch, enabling the Arduino to safely control high voltage loads while maintaining electrical isolation from the low voltage circuitry. Isolation is typically achieved using optocouplers or driver transistors, protecting the microcontroller from voltage surges and ensuring user safety. Prior literature emphasizes the importance of relay-based switching in home automation due to its robustness and compatibility with inductive loads like fans and resistive loads like lamps. Its adoption of smart systems ensures reliable performance, particularly in contexts where affordability and safety are critical considerations. Figure 4 shows a 5V 4 Power Relay Module used for configuration of the proposed work.

Figure 4: A 5V, 4 Power Relay Module

Power Supply Unit:

The power supply unit regulates an input of 9V DC down to 5V using an LM7805 linear regulator and filter capacitors, ensuring stable operation of the Arduino and Bluetooth module. Power regulation is essential for protecting sensitive electronic components from voltage fluctuations, especially in regions with unstable mains supply. Studies stress that integrating reliable power conditioning components enhances the durability of smart home systems, as poor regulation often leads to overheating, system resets, or permanent component failure. Figure 5 shows the block diagram for the Power Supply Unit implemented for the proposed Home Automation System.

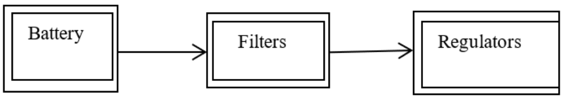

Figure 5: Block Diagram of a Power Supply Unit.

Load:

The system controls common domestic loads such as AC bulbs, fans, and power sockets through the relay interface. These represent typical household appliances that benefit from remote switching for convenience, safety, and energy management. Literature indicates that smart control of such loads contributes significantly to energy savings and demand side management in residential sectors. By targeting these everyday devices, the system demonstrates the practical applicability of Bluetooth-based automation in enhancing comfort and reducing wastage. The proposed Circuit diagram used for implementation of the Home Automation System is shown in Figure 6.

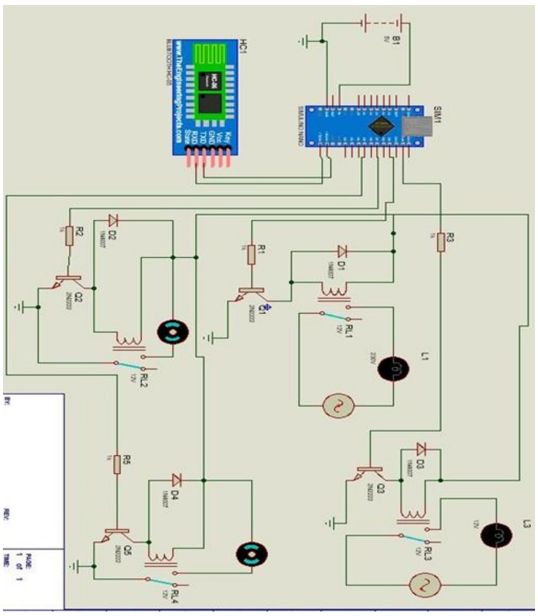

Figure 6: Circuit Diagram of the Smart Home Automation System.

SOFTWARE IMPLEMENTATION:

The software for the system was implemented using the Arduino Integrated Development Environment (IDE), which provides an open-source platform for developing and uploading C/C++ firmware to Arduino Nano. The program initializes serial communication via the Universal Asynchronous Receiver-Transmitter (UART) interface, enabling the HC-05 Bluetooth module to transmit and receive ASCII based commands from the smartphone. These commands are parsed and mapped into corresponding relay activation routines, allowing real-time switching of appliances. Studies emphasize that the simplicity and flexibility of the Arduino IDE, coupled with extensive community libraries, reduce development time and encourage rapid prototyping in home automation applications (Kumar et al., 2020; Sriskanthan et al., 2002). Similar works demonstrate that structured code, employing modular functions and interrupt driven routines, improves system responsiveness and reliability compared to linear command processing (Han et al., 2010). Furthermore, the adoption of lightweight serial communication aligns with findings by Collotta and Pau (2015), who noted that low overhead protocols enhance energy efficiency and responsiveness in microcontroller driven smart home systems. Thus, the software implementation ensures seamless integration between user commands and hardware execution while maintaining simplicity, scalability, and robustness. Figure 7 shows the flow chart implementation of the proposed Smart Home Automation System.

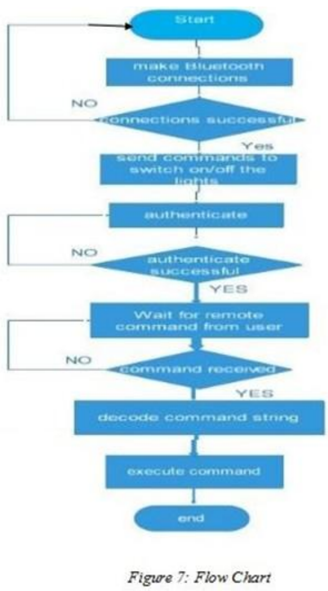

Figure 7: Flow chart of the Smart Home Automation System.

IV. RESULTS AND DISCUSSION

This section discusses the design of the prototype to full implementation of the Home Automation System on Veroboard, and testing using a mini-DC Fan.

Prototype Construction:

The circuit was first simulated to validate switching response, voltage stability, and relay operation before physical construction on Veroboard. The construction of the Smart Home Control Device project was implemented by selecting appropriate components based on calculations and analysis. The hardware was initially assembled on a breadboard, later transferred to a Veroboard, and finally enclosed in a 3D printed casing for durability and user safety as shown in Figure 8.
Figure 9 shows the implementation of the prototype on a Breadboard during testing with a mini–DC Fan. As shown in Figure 10 is the complete implementation of the Automated Home Control Device on a Veroboard with a mini-DC Fan under testing.

Testing and Results:

Successful Bluetooth pairing between smartphone and HC-05.
Relay modules switched both AC and DC loads reliably.
Stable 5V regulated power supply achieved.
Appliance switching response time < 1 s.
Operating range achieved: 10 –12 meters indoors.

Figure 8: 3D Printed Casing Implementation of the proposed Automated Home Control Device.

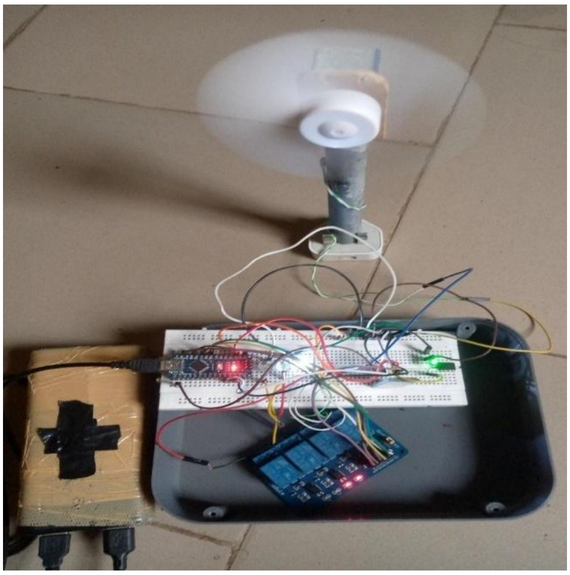

Figure 9: Prototype Implementation and Testing of the Circuit with a Mini DC Fan.

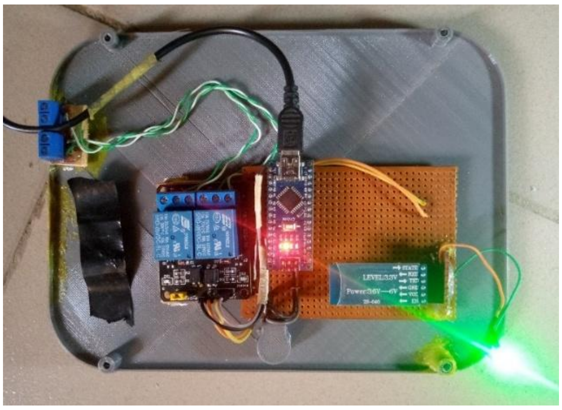

Figure 10: Implementation of the Working Circuit with a Mini DC Fan during Testing.

V. DISCUSSION AND CONCLUSION

The proposed system achieved its primary objectives of safety, reliability, and energy efficiency. By adopting Bluetooth as the communication medium, the design offered a low-cost and straightforward solution compared to Wi-Fi or ZigBee, making it especially attractive in contexts where infrastructure and budgets are constrained. The trade-off lies in communication range: while adequate for small- to medium-sized households, Bluetooth's limited coverage restricts applicability in larger or multi-storey environments unless extended with repeaters or hybrid configurations. Implementation challenges, including initial Arduino code upload errors and mobile app connectivity issues, highlighted common difficulties in microcontroller prototyping. These challenges underscore the need for more streamlined development tools and standardized mobile interfaces. Despite this, the system demonstrated stable, real-time control of both AC and DC appliances, consistent switching response, and reliable voltage regulation.

A notable strength of the system is accessibility. Unlike Internet-enabled IoT solutions that often require continuous connectivity, cloud services, or more costly hardware, the Bluetooth-based approach reduces dependency on external infrastructure. This makes it highly suitable for households in developing countries, where affordability and connectivity are major barriers to technological adoption. At the same time, the modular architecture provides a pathway for future enhancements, including multi-protocol support and cloud integration.

In conclusion, the study confirms that Bluetooth-enabled automation systems can serve as an effective entry point to smart living. They provide immediate, affordable improvements in household safety, convenience, and energy management, while offering a scalable foundation for more advanced IoT integration. Future work should explore hybrid communication modules to overcome range limitations, develop more user-friendly mobile interfaces, test scalability in larger households, and conduct long-term energy profiling to reinforce sustainability claims. Together, these directions can transform simple Bluetooth-based systems into robust smart home solutions that balance inclusivity, functionality, and innovation.

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