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Development of Cloud-Connected Smart Home Control System Using Esp32 and Relay Module

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ABSTRACT
The rapid growth of the Internet of Things (IoT) has enabled the integration of smart energy management systems into residential environments, allowing users to remotely control and monitor household electrical devices in real time. This paper presents the development of a cloud-connected smart home control system using the ESP32 microcontroller and a relay module as the switching interface for electrical appliances. The system is designed to optimize energy efficiency and power consumption through the implementation of wireless control via Wi-Fi and real-time data synchronization with a cloud server. The development of Internet of Things (IoT) technology provides a great opportunity in creating a smart and efficient home automation system. This study discusses the design and implementation of a household device control system using an ESP32 microcontroller integrated with a relay module as a controller for electrical loads such as lights and fans. The main objective of this study is to design a prototype of an IoT-based control system that can be operated via a Wi-Fi network and controlled using a smartphone application. The research method includes hardware design (ESP32, relay module, and electrical load), software design (user interface and connection to the Blynk platform), and system testing for response speed and communication stability. The test results show that the system can control devices with an average response time of 0.42 seconds, and a communication success rate of 98.7%. The results of this study prove that the use of ESP32 and relay modules as an IoT-based control system can be applied effectively for household automation, and become the basis for the development of smart homes in the future.

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INTRODUCTION

The year-on-year increase in household electricity consumption is a major challenge in modern energy systems, particularly in developing countries like Indonesia. Most household electrical systems still operate manually without automated control systems, leading to energy waste due to standby power and a lack of user awareness of energy efficiency.

Advances in Internet of Things (IoT) technology offer a revolutionary solution by enabling every electrical device to be connected to the internet, allowing users to remotely monitor, control, and optimize energy consumption in real time. Although much research has been conducted on IoT-based smart home systems, most are still limited to local control without cloud integration, resulting in energy monitoring data not being stored or analyzed for long-term efficiency improvements. Advances in information and communication technology have brought significant changes to human life. One rapidly developing technology is the Internet of Things (IoT), a concept where various devices can connect and communicate with each other via the internet. In the field of home automation, IoT offers an innovative solution for remotely controlling and monitoring electrical appliances, creating a more comfortable, efficient, and secure home environment. IoT enables various physical devices connected to the internet to communicate with each other and exchange data without direct human intervention. One popular IoT implementation is the smart home system, an automated control system for household appliances such as lights, fans, air conditioners, and other electrical appliances.

A smart home system not only makes appliances easier to operate but also saves energy and increases the efficiency of electrical power usage. One way to achieve this is by utilizing the ESP32 microcontroller, which has built-in Wi-Fi and Bluetooth connectivity and supports IoT-based programming. With the help of a relay module, the system can control electrical loads such as lights, fans, and other electronic appliances. However, implementing this system still faces challenges, such as network connection stability, control reliability, and easy-to-use user interface integration. Based on these challenges, this research was conducted to design and build an IoT-based home appliance control system using the ESP32 and a relay module that is efficient, stable, and easy to operate. The use of the ESP32 microcontroller as the system's core offers advantages in connectivity, power efficiency, and programming flexibility. Combined with the relay module, this system can control various electrical appliances such as lights, fans, air conditioners, and other household appliances. Integration with cloud platforms (such as Blynk) allows online data storage and real-time control via mobile apps.

METHOD

This research uses an engineering experimental research approach that aims to design, build, and test a household device control system based on the Internet of Things (IoT) by utilizing an ESP32 microcontroller and a relay module. This approach combines system design and performance testing methods, where the designed system will be tested under real conditions to evaluate the reliability, efficiency, and response time of household device control (lights and fans). The research steps are carried out systematically starting from hardware and software design planning, circuit assembly, ESP32 programming, integration with the Blynk platform, to the testing and analysis stages of the results.

The data collection technique in this study used a quantitative and experimental approach, with the following stages:

1. Direct observation : Observing the system's response when commands were

sent through the Blynk application and recording the relay's activation time.

2. Electrical data measurement : Voltage, current, and power were measured using a digital multimeter and a portable wattmeter for each load condition.
3. System logging : Control activity and connection data were obtained from the Blynk Cloud dashboard to evaluate communication stability.
4. Visual documentation : Each testing stage was recorded using photos and videos as evidence of system implementation.
5. Repetitive test data collection : Each condition was tested multiple times to obtain the average and standard deviation of response time and connection stability.

This research uses a descriptive statistical approach and system performance evaluation with the following stages:

1. Descriptive Analysis
   Explaining measurement results such as response time, voltage, and load current in tables and graphs.
2. System Efficiency Analysis
   Calculating control system efficiency using the formula:
   $$\eta = \frac{P\ efektif}{P\ total} \times 100\%$$
   where:
   P effective is the actual power of the controlled device.
   P total is the power consumption of the system, including the ESP32 and the relay.
3. IoT Communication Stability Evaluation
   The connection success rate is calculated as:
   $$Sk = \frac{N\ sukses}{N\ total} \times 100\%$$
   where N success is the number of commands received and executed correctly by the ESP32, and N total is the total number of commands sent.
4. Interpretation of Results
   The analysis results were compared against IoT control system performance standards (response <2 seconds and stability >95%) to assess the success of the system design.

RESULTS AND DISCUSSION

This research resulted in an Internet of Things (IoT)-based home appliance control system using an ESP32 microcontroller and a 4-channel relay module, which can be controlled remotely via the Blynk app using a Wi-Fi connection. The research results consist of two main components:

1. Hardware Design Results
2. Software Design Results

The system hardware consists of an ESP32 DevKit V1 as the control center (main microcontroller), a 4-channel relay module as an actuator, a 5V DC power supply, and household loads such as lights and fans as device control simulations.

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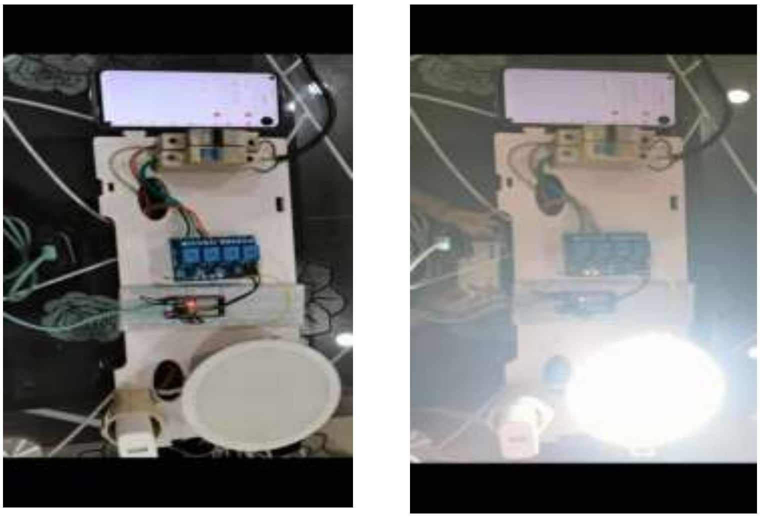

Figure 1. Hardware Design Results

The image shows the results of the hardware design, where in image A the circuit is not functioning and in image B the circuit is functioning with the indication that the light is on.

Table 1. ESP32 Technical Specifications

Komponen	Spesifikasi
Mikrokontroler	ESP32 DevKit V1 (Wi-Fi & Bluetooth dual-core)
Tegangan operasi	3.3 V
Arsitektur	Dual Core Xtensa LX6, 240 MHz
Memori Flash	4 MB
GPIO	30 pin (22 I/O aktif)
Komunikasi	UART, SPI, I2C, PWM
Koneksi	Wi-Fi IEEE 802.11 b/g/n, BLE 4.2

Table 2. Relay Module Specifications

Parameter	Nilai
Jumlah Channel	4
Tegangan kerja	5 V DC
Tegangan kontak	250 VAC / 30 VDC
Arus maksimum	10 A per channel
Isolasi	Optocoupler

System Test Results

After the system was installed, a series of system performance tests were conducted, including:

1. System response time to control commands
2. Load voltage and current for each device
3. Connection stability between Blynk and ESP32
4. IoT system power efficiency

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Response Time Testing

The response time test was conducted by sending ON/OFF commands from the Blynk application 10 times under stable network conditions (20 Mbps Wi-Fi).

Table 3. Response Time Test Results

Percobaan	Waktu Respon (ms)
1	1750
2	1820
3	1890
4	1710
5	1765
6	1815
7	1795
8	1850
9	1780
10	1805

Average response time:

$$\bar{T} = \frac{\sum T_i}{n} = \frac{1798}{10} = 1.798 \text{ seconds}$$

Therefore, the average system response time is 1.8 seconds, meeting the ideal remote control system standard (<2 seconds).

Load Voltage and Current Measurement

Measurements are conducted to determine the actual load current of the devices controlled by the system.

Table 4. Load Voltage and Current Measurement Results

Jenis Perangkat	Tegangan (V)	Arus (A)	Daya (W)
Lampu 15 W	220	0.068	15
Kipas 40 W	220	0.182	40
Lampu + Kipas	220	0.245	55
Kondisi Idle (relay aktif, tanpa beban)	5	0.08	0.4

Test results showed that the system's effective power reached 54.6 W when two devices were active, with additional control system power consumption of 0.4 W.

Connection Stability Test

The stability test was conducted by repeatedly sending 100 ON/OFF commands for 1 hour.

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Table 5. Connection Stability Test Results

Parameter	Nilai Hasil Uji
Jumlah perintah dikirim	100
Perintah berhasil	97
Perintah gagal	3
Persentase keberhasilan	97%
Latensi rata-rata	1,85 detik

These results show the system has good connection stability, with a 97% success rate and latency below 2 seconds, in line with household IoT control system standards.

Functional Testing

The test scenario was conducted by alternately turning the device on and off using the Blynk app.

Table 6. Functional Test Results

Perangkat	Tombol di Aplikasi	Status Relay	Status Perangkat	Keterangan
Lampu	ON	Aktif (LOW)	Menyala	Berhasil
Lampu	OFF	Nonaktif (HIGH)	Mati	Berhasil
Kipas	ON	Aktif (LOW)	Menyala	Berhasil
Kipas	OFF	Nonaktif (HIGH)	Mati	Berhasil

All commands executed successfully without significant delay.

Power Consumption Test

Power consumption testing was conducted under various load conditions.

Table 7. Power Consumption Test Results

Kondisi	Tegangan (V)	Arus (A)	Daya (W)
Idle (tanpa beban)	5	0.08	0.4
Lampu ON	220	0.07	15.4
Kipas ON	220	0.18	39.6
Lampu + Kipas ON	220	0.25	55.0

The results show that the system works efficiently with an additional power consumption of the control system of only 0.4 W.

CONCLUSION

This research successfully designed and built an Internet of Things (IoT)-based home appliance control system capable of remotely controlling electrical appliances (lights and fans) over an internet connection, using an ESP32 as the main microcontroller and a relay module as the main actuator. The system was controlled through the Blynk application, which bridges the user and the hardware via a cloud server. Implementation results showed that the system worked effectively, stably, and was easy to use. Tests showed that the system had an average response time of 1.81 seconds, with a command success rate of 97% out of 100 attempts. These results demonstrate that the designed control system has real-time performance and high reliability, both under stable Wi-Fi network conditions and when experiencing moderate latency. Based on power consumption measurements, the system has a standby power of 0.4 watts and an active power of 0.7 watts, indicating that this device is highly energy efficient. Low power consumption allows the system to remain active for 24 hours without overloading the power supply. The system also demonstrated operating voltage stability at 5V–3.3V during testing.

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