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Design and Development of IoT-Based Smart Street Lighting with Lighting Level Adjustment Based on Environmental Sensors

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Abstract

This research discusses the design of an Internet of Things (IoT)-based Smart Street Lighting system that is able to adjust lighting levels automatically based on environmental conditions. The system is implemented on a garden lamp prototype by utilizing Light Dependent Resistor (LDR) and Passive Infrared (PIR) sensors as the main input in regulating lamp intensity. The ESP32 microcontroller is used as a control center as well as an IoT communication module for monitoring and controlling the system through a real-time web interface. The research method used is prototyping which includes hardware design, software development, implementation, and system testing. The test results show that the system is able to regulate lighting automatically, namely the lights turn off in bright conditions, turn on dimly when dark conditions with no activity, and turn on brightly when activity is detected. In addition, the web-based monitoring system successfully displays the status of the lights and sensors in real-time. The developed system can be a more efficient, adaptive outdoor lighting solution and supports the application of IoT technology in smart lighting systems.

***Keywords:** ESP32, IoT, LDR, PIR, Smart Street Lighting*

1. Introduction

Outdoor lighting plays an important role in improving safety, comfort, and security in public environments during nighttime. One of the most common forms of outdoor lighting is park lighting, which not only provides illumination but also supports social activities, recreation, and environmental aesthetics. However, most conventional outdoor lighting systems operate using fixed illumination levels regardless of environmental conditions or user presence. As a result, electrical energy is often consumed inefficiently because lamps remain illuminated at the same intensity even when lighting demand is low. Recent developments in LED-based outdoor lighting technologies have focused on improving energy efficiency and operational performance to address increasing energy consumption concerns [1].

Recent advances in the Internet of Things (IoT) have enabled the development of smart lighting systems capable of adapting to changing environmental conditions. Smart street lighting has become an important component of smart city initiatives due to its ability to improve energy efficiency and operational flexibility. IoT-based lighting systems can automatically adjust lighting conditions based on real-time sensor data, resulting in more efficient energy utilization than conventional lighting systems [2], [3]. Furthermore, the integration of environmental sensing and intelligent control mechanisms allows lighting levels to be adjusted according to actual field requirements, thereby reducing unnecessary power consumption [3]. IoT technology provides interconnected communication among devices, enabling remote monitoring and autonomous operation of smart infrastructure systems [4].

Environmental sensors play a significant role in the implementation of adaptive lighting systems. Light sensors are commonly used to measure ambient illumination, while motion sensors detect user activity within the monitored area. Information obtained from these sensors serves as the basis for automated lighting decisions. Previous studies have demonstrated that combining light sensing and motion detection technologies can improve energy efficiency by activating higher illumination levels only when required [3], [5]. LDR sensors have been widely utilized in automatic lighting systems because of their ability to detect changes in environmental light intensity with reliable sensitivity [6], [7]. Likewise, PIR sensors have become a common solution for motion detection applications due to their effectiveness in identifying human activity within a monitored area [8].

In addition to automatic control, monitoring capability has become an essential requirement in modern smart lighting applications. Cloud-connected lighting systems enable operators to observe lamp conditions and system performance remotely through web-based interfaces [9]. Digital connectivity also improves system management by allowing centralized monitoring and real-time data acquisition [10]. Moreover, recent studies have explored the integration of IoT communication technologies to support reliable remote monitoring and control of outdoor lighting infrastructures [11]. Although numerous studies have investigated IoT-based smart lighting systems, most of them focus primarily on public street lighting or emphasize monitoring and control functions independently. Research specifically addressing adaptive park lighting systems that integrate Light Dependent Resistor (LDR) sensors, Passive Infrared (PIR) sensors, Pulse Width Modulation (PWM)-based brightness control, and web-based monitoring within a single platform remains limited. Furthermore, many existing studies focus on large-scale smart city implementations, whereas practical prototype-based solutions for localized outdoor lighting applications are less frequently discussed.

Therefore, this study proposes the design and development of an IoT-based Smart Street Lighting system implemented on a park lighting prototype using an ESP32 microcontroller. The proposed system integrates LDR and PIR sensors to automatically adjust lighting levels according to ambient light conditions and user activity. In addition, a web-based monitoring platform is developed to provide real-time visibility of system status. The contribution of this research lies in the integration of adaptive lighting control, environmental sensing, and IoT-based monitoring into a compact prototype that supports energy-efficient outdoor lighting applications and contributes to the advancement of smart city technologies.

2. Research Method

This research employed the prototyping method to develop an Internet of Things (IoT)-based Smart Street Lighting system. The prototyping approach was selected because it allows iterative system development through design, implementation, testing, and refinement stages until the desired functionality is achieved. The proposed system was developed as a park lighting prototype capable of automatically adjusting illumination levels according to environmental conditions and user activity.

2.1. Literature Study

The initial stage of the research involved reviewing relevant literature from journals, books, and scientific publications related to smart street lighting, Internet of Things (IoT), ESP32 microcontrollers, Light Dependent Resistor (LDR) sensors, Passive Infrared (PIR) sensors, Pulse Width Modulation (PWM), and web-based monitoring systems. This stage was conducted to establish the theoretical foundation and determine an appropriate system design.

2.2. System Design

The proposed system consists of hardware and software components integrated to perform automatic lighting control and real-time monitoring.

2.2.1. Hardware Design

The hardware components used in this study include:

1. ESP32 microcontroller as the main controller and IoT communication module.
2. LDR sensor for detecting ambient light intensity [6], [7].
3. PIR sensor for detecting user activity and motion [8].
4. LED lamp as the lighting source.
5. MOSFET IRLZ44N as the LED driver.
6. Power supply and supporting electronic components.

The interaction among system components is illustrated in Figure 1.

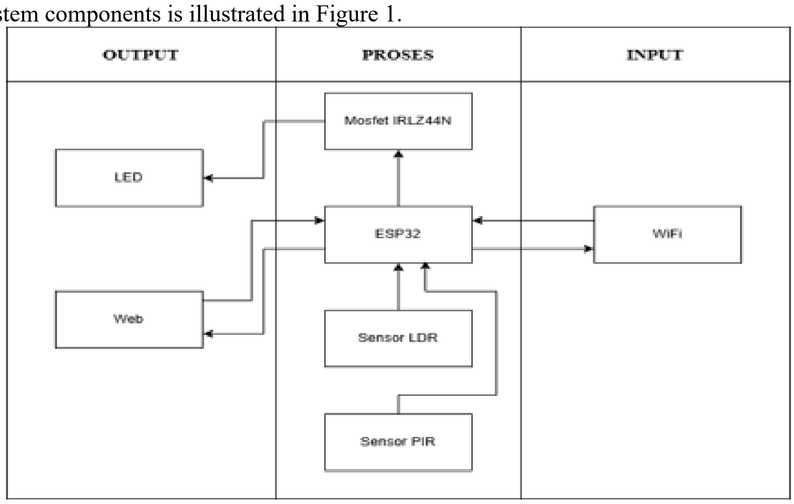

Fig. 1 : Block Diagram

Based on Figure 1, the ESP32 receives input data from the LDR and PIR sensors. The collected information is processed to determine the appropriate lighting level. The ESP32 controls the LED through the MOSFET driver and simultaneously communicates with the web monitoring platform through a Wi-Fi connection.

2.2.2. Software Design

The software was developed using Arduino IDE for ESP32 programming. Firebase Realtime Database was employed as the cloud-based data storage platform, while a web-based interface was developed to provide real-time monitoring and control of the lighting system.

Similar IoT-based monitoring architectures have been successfully applied for remote supervision of electrical systems and smart devices [12], [13].

2.3. System Implementation

The implementation stage involved integrating the hardware and software components into a single operational system. The ESP32 continuously reads data from the LDR and PIR sensors and processes the information to determine the lighting condition. PWM control is applied to regulate LED brightness levels. Pulse Width Modulation (PWM) is widely used in power electronics applications because it enables flexible and efficient control of output power by varying the duty cycle [14]. Sensor data and lamp status are transmitted to Firebase Realtime Database and displayed on the monitoring web interface in real time.

2.4. System Working Mechanism

The operational mechanism of the proposed Smart Street Lighting system was designed to automatically adjust lamp brightness according to ambient light conditions and user activity. The system integrates LDR and PIR sensors as the primary inputs, while the ESP32 microcontroller processes the sensor data and determines the appropriate lighting condition. Furthermore, the system is connected to a web-based monitoring platform through a Wi-Fi network, allowing real-time monitoring and control. The overall operational flow of the system is illustrated in Figure 2.

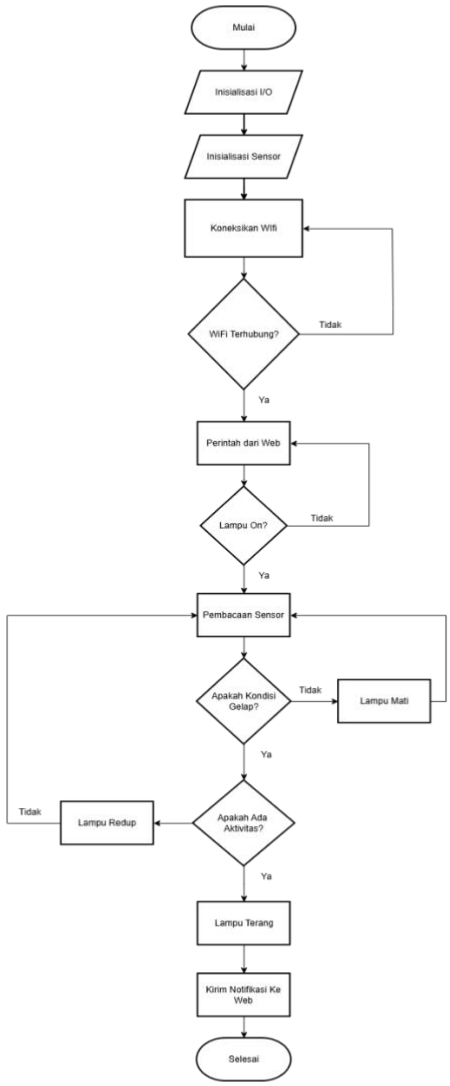

Fig. 2 : Flowchart

The system begins by initializing the input/output ports and environmental sensors, followed by establishing a Wi-Fi connection. Once the connection is successfully established, the ESP32 receives commands from the web interface and continuously monitors environmental conditions through the LDR and PIR sensors. Based on the acquired sensor data, the system determines the appropriate lighting level according to the predefined control logic. The operational logic can be summarized as follows:

1. If the ambient environment is bright, the lamp remains turned off.
2. If the environment is dark and no activity is detected, the lamp operates in dim mode.
3. If the environment is dark and activity is detected by the PIR sensor, the lamp operates in bright mode.
4. Sensor readings and lamp status are transmitted to the web monitoring platform in real time.

This operational mechanism enables the lighting system to adapt to changing environmental conditions while reducing unnecessary energy consumption. In addition, the integration of web-based monitoring allows users to observe system status and control lighting operation remotely through an internet connection.

2.5. System Testing

System testing was conducted to evaluate the functionality and performance of each component. The testing procedures included:

1. LDR sensor testing to evaluate ambient light detection performance.
2. PIR sensor testing to evaluate motion detection capability.
3. Lamp control testing to verify automatic brightness adjustment.
4. Firebase communication testing to evaluate IoT data transmission.
5. Web monitoring testing to verify real-time data visualization and control functionality.

The results of these tests were analyzed to determine the effectiveness and reliability of the proposed Smart Street Lighting system.

3. Results and Discussion

3.1. System Implementation Results

The proposed IoT-based Smart Street Lighting system was successfully implemented as a prototype representing an outdoor park lighting environment. The prototype consists of an ESP32 microcontroller, LDR sensor, PIR sensor, LED lamps, MOSFET IRLZ44N driver, and a web-based monitoring platform. The physical implementation of the developed system is shown in Figure 3.

Fig. 3 : Prototype of the Proposed Smart Street Lighting System

As shown in Figure 3, the prototype was designed to simulate a park lighting environment equipped with multiple lighting points and environmental sensing components. The ESP32 functions as the central controller responsible for processing sensor data and controlling lamp brightness levels. The LDR sensor is used to detect ambient light intensity, while the PIR sensor detects user activity within the monitored area. The LED lamps are controlled through a MOSFET IRLZ44N driver using Pulse Width Modulation (PWM) to achieve different lighting levels according to environmental conditions. Furthermore, the ESP32 communicates with Firebase Realtime Database through a Wi-Fi connection, allowing sensor readings and lamp status information to be displayed on the web monitoring interface in real time. The successful integration of hardware and software components demonstrates that the proposed system can perform automatic lighting control and remote monitoring as intended in the system design.

3.2. LDR Calibration Results

Prior to system testing, the LDR sensor was calibrated to determine the relationship between ADC readings and light intensity values expressed in lux. The calibration process was conducted by measuring the sensor output under different lighting conditions and converting the obtained ADC values into corresponding illumination levels. The calibration results were subsequently used as the basis for defining the lighting thresholds applied in the proposed Smart Street Lighting system. The calibration data obtained during testing are presented in Table 1.

Table 1 : LDR Calibration Results

ADC Value	Environmental Condition
4095	0
2831	3.1
2211	9.8
2055	12
1907	23
1680	28
1580	33
1462	40
1370	47
1201	62

Based on Table 1, the calibration results indicate an inverse relationship between ADC readings and light intensity values. Higher ADC values correspond to lower illumination levels, while lower ADC values indicate brighter environmental conditions. The calibration data were used to establish the lighting thresholds for automatic lamp control in the proposed system.

3.3. LDR Sensor Testing

After the calibration process was completed, the LDR sensor was tested to evaluate its ability to classify environmental lighting conditions based on predefined lux thresholds. The obtained lux values were used to determine the appropriate lamp operating state. The testing results are presented in Table 2.

Table 2 : LDR Sensor Testing Results

Lux Value	Environmental Condition	Lamp Status
> 45 Lux	Bright	OFF
5 – 45 Lux	Dim	Dim
≤ 5 Lux	Dark	ON

Based on Table 2, the proposed system successfully classified environmental lighting conditions according to the defined lux thresholds. When the measured light intensity exceeded 45 lux, the environment was categorized as bright and the lamp remained turned off. For illumination levels between 5 and 45 lux, the system classified the condition as dim and operated the lamp at reduced brightness. When the light intensity was equal to or below 5 lux, the environment was considered dark and the lamp was automatically activated. These results demonstrate that the calibrated LDR sensor can effectively support adaptive lighting control by providing reliable environmental illumination information.

3.4. PIR Sensor Testing

The PIR sensor testing was performed to evaluate the capability of the system to detect user activity within the monitored area. The sensor output was used as one of the primary parameters in determining the lamp brightness level. The testing results are shown in Table 2.

Table 3 : PIR Sensor Testing Results

Condition	PIR Detection	Lamp Status
Activity Detected	Detected	Bright
No Activity	Not Detected	Dim
Activity Detected	Detected	Bright

The PIR sensor successfully detected user activity within the monitored area. When motion was detected, the lighting system increased the illumination level to improve visibility. In the absence of activity, the lamp operated in dim mode to reduce energy consumption. The results demonstrate the effectiveness of PIR sensing for adaptive lighting applications and confirm that the sensor can support adaptive lighting control based on user presence.

3.5. Web Monitoring Testing

The web monitoring system was tested to evaluate its ability to display sensor data and lamp status information in real time. The developed monitoring platform provides users with access to environmental conditions, lighting status, and manual control functions through an internet connection. The main monitoring interface is shown in Figure 4.

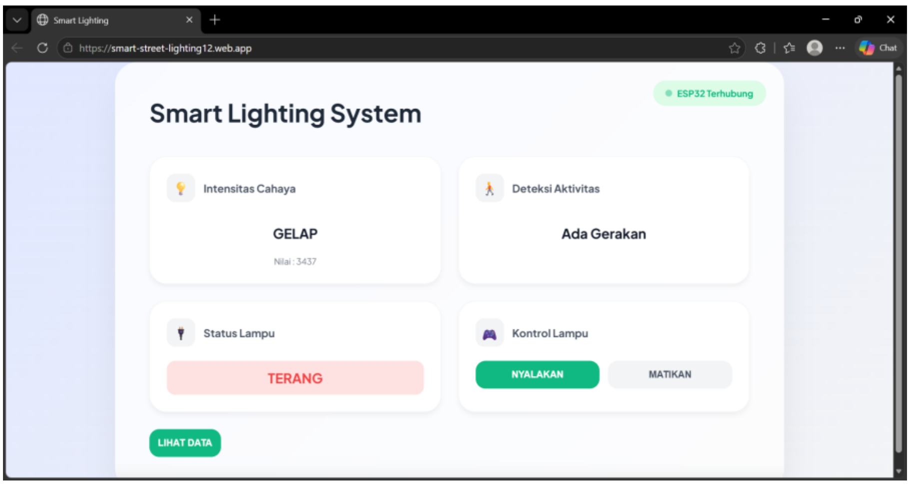

Fig. 4 : Web-Based Monitoring Interface

Figure 4 presents the developed web-based monitoring interface. The platform displays real-time information regarding ambient light intensity, motion detection status, lamp operating conditions, and ESP32 connectivity. The interface also provides manual control functionality, allowing users to remotely switch the lamp on or off. During testing, data transmission between the ESP32 and Firebase Realtime Database was successfully performed, and all monitored parameters were updated in real time.

In addition to real-time monitoring, the system also provides a historical data page that allows users to review previously recorded sensor readings and lamp status information. This feature enhances monitoring capabilities by enabling users to evaluate system performance over time. The historical data monitoring interface is shown in Figure 5.

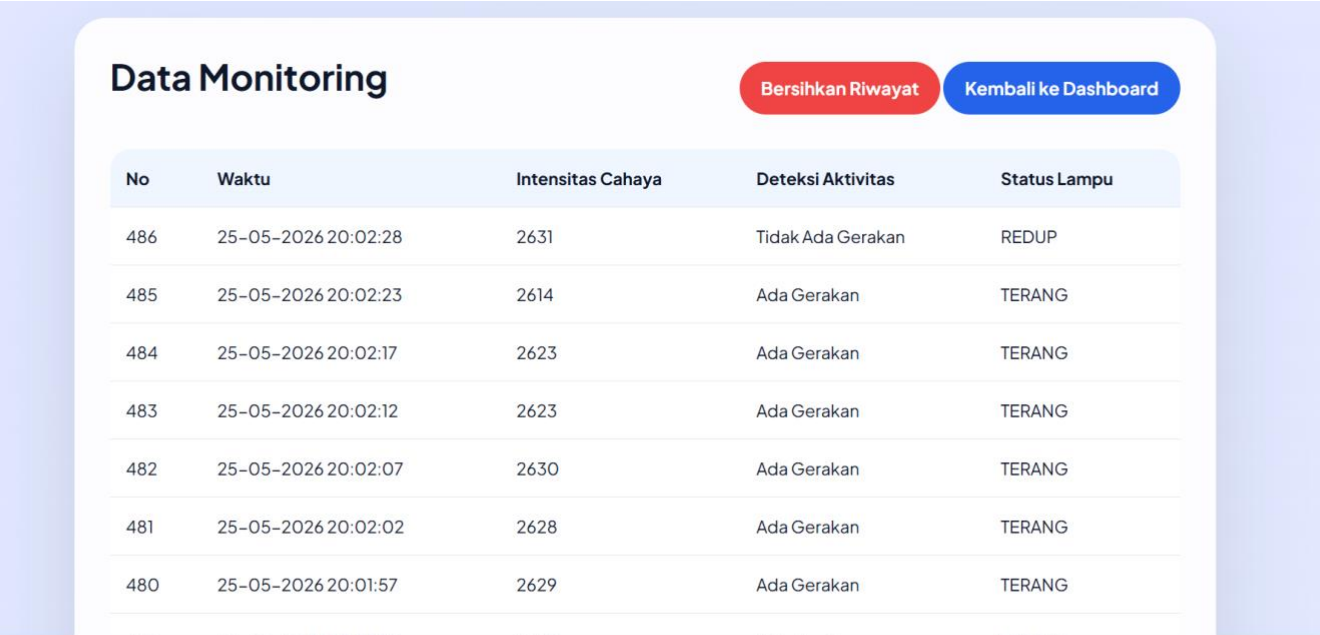

Fig. 5 : Historical Data Monitoring Page

The historical data monitoring page allows users to access previously recorded sensor readings and lamp status information stored in Firebase Realtime Database. Through this interface, users can review environmental conditions, motion detection records, and lamp operating states at different periods. The availability of historical data provides additional information for evaluating system performance and verifying the consistency of lighting control operations.

During testing, all data transmitted by the ESP32 were successfully stored and displayed on the historical monitoring page. The recorded information matched the actual conditions detected by the LDR and PIR sensors, indicating that the data transmission and storage processes functioned properly. Furthermore, the web application was able to retrieve and display stored records without significant delays.

Overall, the web monitoring system successfully provided both real-time monitoring and historical data visualization functionalities. The integration of ESP32, Firebase Realtime Database, and the web-based interface enabled users to monitor environmental conditions, control lamp operation, and review historical records remotely. These results demonstrate that the proposed IoT-based monitoring platform can effectively support the operation and management of the Smart Street Lighting system.

4. Conclusion

This study successfully designed and implemented an Internet of Things (IoT)-based Smart Street Lighting system capable of automatically adjusting illumination levels according to ambient light conditions and user activity. The proposed system integrates an ESP32 microcontroller, LDR sensor, PIR sensor, PWM-based LED control, and a web-based monitoring platform to provide adaptive outdoor lighting functionality.

The experimental results confirmed that the system operated according to the designed control logic, where the lamp remained OFF during bright conditions, operated in DIM mode during dark conditions without activity, and switched to BRIGHT mode when motion was detected. The integration of LDR and PIR sensors enabled adaptive lighting control, contributing to more efficient energy utilization compared with conventional fixed-intensity lighting systems

Furthermore, the implementation of Firebase Realtime Database and the web monitoring platform successfully provided real-time monitoring, remote control, and historical data visualization. These features enhance system accessibility and facilitate monitoring of lighting performance through internet connectivity.

Overall, the developed prototype demonstrates the feasibility of implementing intelligent, adaptive, and energy-efficient outdoor lighting systems. The proposed approach can serve as a practical foundation for future smart lighting applications and support the development of smart city infrastructure.

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