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Analysis of the Effectiveness of IoT-Based Automatic Street Lighting Control Using Linear Regression Method

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Abstract: Public street lighting (PJU) is a crucial component of infrastructure that ensures security during nighttime. This research aims to design an automatic PJU control system utilizing Internet of Things (IoT) technology, employing light and motion sensors integrated with an ESP32 microcontroller. The system enables remote control of PJU lamps via a web-based platform, offering significant flexibility for users. The ESP32 microcontroller is linked to a PIR sensor that detects motion, which triggers an increase in the intensity of the PJU lamps. Conversely, when no motion is detected, the light intensity is reduced to conserve energy. Users can manage the PJU lamps from any internet-connected device. Experimental results demonstrate a notable improvement in energy efficiency, with an average reduction in power consumption of 13.77 watts and an efficiency increase of 42.67%. The linear regression model employed yields an R-squared value of 0.629, indicating a reasonably good fit in explaining the variability in power consumption. This system offers real-time monitoring and autonomous operation of street lights, contributing to the advancement of smarter and more efficient PJU systems.

Keywords: Public Street Lighting (PJU); Internet of Things (IoT); Sensor; ESP32 Microcontroller; Linear Regression.

1. Introduction

Public street lighting (PJU) is a crucial infrastructure component that plays a vital role in ensuring the safety and comfort of the community, particularly during nighttime. PJU not only supports nighttime activities but also significantly reduces the risk of traffic accidents and deters criminal activities. In densely populated urban areas, such as in Indonesia, adequate lighting is essential for maintaining public order and safety. However, the effectiveness of existing PJU systems is often questioned, particularly in areas that still rely on conventional methods of management [1]. In several residential complexes, including Pondok Ungu Permai in Bekasi, the PJU systems are largely manual, where on-off switches are used to control lighting. Additionally, some semi-automatic systems rely solely on timers and light sensors. While these systems are more advanced than fully manual controls, they still have significant weaknesses regarding energy efficiency and responsiveness to environmental changes. Static timers cannot adjust to actual conditions on the ground, and light sensors only respond to brightness levels without considering human activity in the vicinity.

The issues of low energy efficiency and lack of responsiveness are critical concerns in PJU management, particularly in an era where efficient energy use is becoming increasingly urgent. In this context, there is a growing need to develop smarter and more adaptive PJU control systems that can adjust lighting intensity in real-time based on environmental conditions. One technology that can be leveraged to achieve this is the Internet of Things (IoT). IoT offers a solution by integrating various sensors that can communicate and interact in real-time through the internet. In this research, IoT technology is employed to develop an automatic control system for PJU, utilizing the ESP32 microcontroller as the central control unit. This microcontroller is chosen for its robust connectivity capabilities and support for multiple sensors, such as light and motion sensors. The light sensor detects ambient brightness levels, while the motion sensor (PIR) detects human activity in the area surrounding the PJU. By utilizing data from these two sensors, the system can automatically adjust the intensity of the PJU lamps, increasing or decreasing brightness based on actual needs on the ground.

This study aims to analyze the effectiveness of the IoT-based automatic PJU control system, particularly in terms of energy efficiency and responsiveness to environmental changes. The use of linear regression methods in data analysis allows for the measurement of relationships between variables involved, such as energy consumption levels and motion detection. Thus, the system is expected not only to improve energy efficiency but also to be reliable under various dynamic environmental conditions. The proposed PJU control system is anticipated to provide a more efficient and intelligent solution compared to the conventional methods currently in place. Additionally, the ability to monitor and control the system in real-time remotely via a web-based platform offers users high flexibility in managing public lighting. Through the implementation of IoT technology, it is expected that there will be a significant improvement in energy management and security in areas that adopt this automatic PJU control system.

2. Research Method

This research on the IoT-based automatic control system for public street lighting (PJU) is conducted through a series of methodical steps, which include a literature review, system design, system implementation, data collection, data preprocessing, data analysis, and concluding with recommendations. Each of these steps is critical to ensure the development of an efficient and responsive PJU system that leverages modern IoT technologies.

2.1 Literature Review

The literature review forms the foundational basis for this research, providing a comprehensive understanding of existing technologies and methodologies relevant to the study. The review focuses on the principles of automatic control systems and the Internet of Things (IoT). Automatic control systems are integral to various industries, acting as the core of production and distribution processes. These systems are designed to operate autonomously, significantly reducing the need for human intervention, thereby enhancing efficiency and lowering operational costs [2][3][4]. IoT, or the Internet of Things, refers to a network of interconnected devices that communicate with each other and with cloud-based systems. Within the context of PJU, IoT enables real-time communication between sensors and control systems, facilitating data exchange and automated decision-making. IoT systems typically involve a network of "things" that, while not directly connected to the internet, communicate via internet connections to transmit and receive data. This connectivity allows IoT devices to execute actions based on real-time data, which is essential for optimized operations. A common example of IoT application is smart home lighting, which can be controlled remotely through a smartphone. In broader terms, IoT allows various devices to connect and communicate over the internet, driving innovations and efficiencies in numerous aspects of daily life [5][6][7][8].

2.2 System Design

The system design phase is crucial as it involves conceptualizing and detailing the architecture of the PJU control system. In this research, the prototyping method is employed to design the IoT-based automatic PJU control system. The prototyping approach starts with requirement gathering, which involves collaboration between developers and users to clearly define the system's objectives, functionalities, and operational needs [9]. This ensures that the final design is not only technologically advanced but also practical and user-oriented [10]. The system's architecture is built around the ESP32 microcontroller, chosen for its robust connectivity and support for various sensors. The design process includes the creation of flowcharts that detail the system's operation, particularly focusing on how the system responds to environmental changes (see Figure 1).

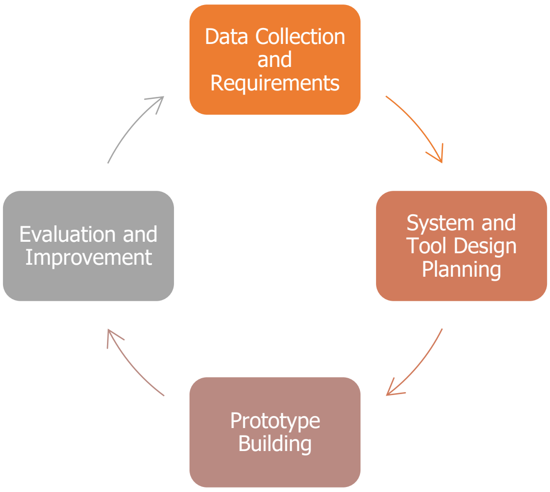

Figure 1. Prototype Method

The system incorporates two primary methods for controlling the PJU lights. First, the lights are programmed to automatically turn on when there is a decrease in ambient light intensity, ensuring illumination during darker periods, such as nighttime. Additionally, the system offers remote control capabilities through a web-based application, providing flexibility for users to manage the lighting system remotely. For situations where internet connectivity is unavailable, a manual switch is included as a backup. The system employs two main sensors: a light-dependent resistor (LDR) sensor that measures ambient light levels, and a passive infrared (PIR) sensor that detects motion. When the ambient light falls below a certain threshold, the system identifies the need for additional lighting and activates the lights automatically.

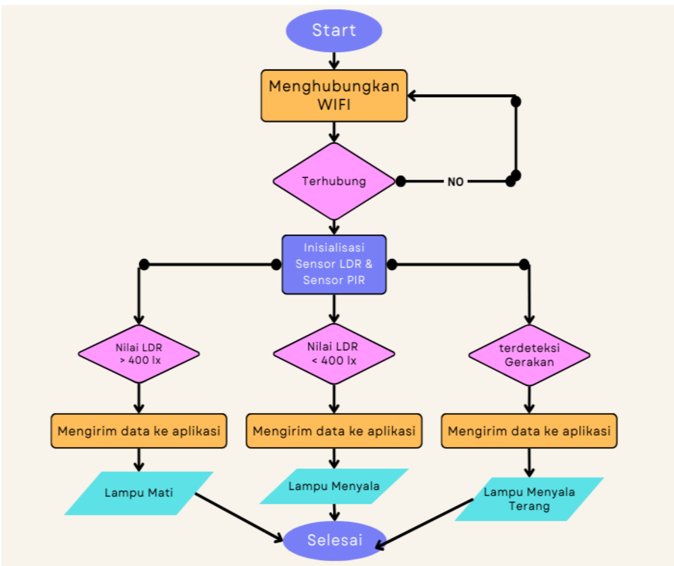

Figure 2. Flowchart of IOT-based control system

2.3 Hardware Design

The hardware design phase involves the creation and assembly of the physical components required for the IoT-based automatic PJU control system. This includes the development of a prototype that integrates key components such as the LDR and PIR sensors, the ESP32 microcontroller, and other essential modules. The LDR sensor measures light intensity, while the PIR sensor detects motion in the surrounding area. The data from these sensors are processed by the ESP32 microcontroller, which determines whether the lights should be turned on or off. The microcontroller then controls a relay that manages the light switching based on the processed data. Additionally, a PZEM module is used to measure power consumption and energy usage, with this data being transmitted to a web server via the ESP32. This setup allows users to remotely monitor and control the system through an internet connection. The overall hardware configuration is depicted in the wiring diagram shown in Figure 2.

2.4 System Implementation

System implementation is the phase where the system design is actualized by integrating the hardware and software components. This phase includes assembling the prototype, connecting all the hardware components, and testing their functionality. The implementation also involves developing the software that will control the system, including a web-based interface for monitoring and managing the PJU lights. The software displays data from the sensors, such as light intensity, PIR sensor status, and electrical metrics like voltage, current, power (watts), and energy consumption (kilowatt-hours). It also provides users with the ability to remotely control the lights, offering on/off capabilities from a distance. The steps involved in implementing both hardware and software components are illustrated in Figures 3 and 4, respectively.

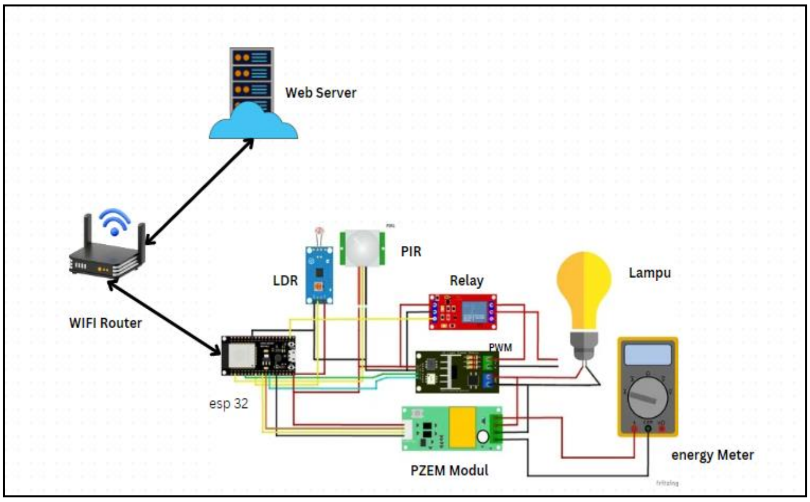

Figure 3. Wiring Diagram of Automatic Control System

2.5 Data Collection

Data collection is a critical step that provides the necessary information for validating the system's performance and effectiveness. Data is gathered using the IoT-enabled ESP32 microcontroller, equipped with key sensors such as motion sensors, light sensors, pulse-width modulation (PWM) modules, and voltage, frequency, and current measurement modules. The collected data includes real-time readings of environmental conditions, power usage, and system performance metrics. This data serves as the basis for further analysis and is essential for evaluating the system's energy efficiency and responsiveness to changes in the environment.

2.6 Data Preprocessing

Before data analysis can be conducted, the collected data must undergo preprocessing to ensure its quality and reliability. Data preprocessing involves cleaning, normalizing, and reducing noise in the data. Data cleaning removes any erroneous or irrelevant data points that may have resulted from sensor errors or anomalies. Normalization is applied to standardize the data, making it easier to analyze and interpret. Noise reduction techniques are also employed to minimize the impact of random fluctuations in the data, ensuring that the final dataset is accurate and representative. This preprocessing stage is crucial for producing clean, reliable data that can be used for accurate analysis.

2.7 Simple Linear Regression Analysis

Simple linear regression analysis is employed to predict energy consumption based on inputs from the motion sensor. The primary goal of this analysis is to evaluate the system's effectiveness in optimizing energy use when the lighting system is activated based on actual needs (motion detection). In this model, energy consumption (measured in watts) is the dependent variable (Y), while the motion sensor's status (whether it detects motion or not) is the independent variable (X). The simple linear regression model can be mathematically expressed as follows:

$$Y = a + bX$$

Where:
Y represents the dependent variable (energy consumption in watts),
X represents the independent variable (PIR sensor state),
a is the intercept (the value of Y when X=0),
b is the slope (the average change in Y for each unit change in X).

2.8 Model Validation and Evaluation

Model validation is an essential step to ensure the accuracy and reliability of the regression model developed. Validation is conducted using a subset of the data or through cross-validation techniques, which help to verify that the model generalizes well to new, unseen data and is not overfitting the training data. Additionally, residual analysis is performed to ensure that the model meets the basic assumptions of linear regression, including linearity, independence, homoscedasticity, and normality of residuals. The validation and evaluation process includes several key metrics:

1) Mean Squared Error (MSE)
   MSE is calculated using the mean_squared_error function from the sklearn.metrics library. It provides a measure of the average squared difference between the actual values (from the test set) and the predicted values. A lower MSE indicates a better fit of the model to the data.
2) R-squared (R^2)
   R-squared is calculated using the r2_score function from sklearn.metrics and indicates how well the model explains the variability in the data. R^2 is the coefficient of determination and ranges from 0 to 1, with higher values indicating a better model fit. An R^2 value close to 1 suggests that the model explains most of the variability in the response variable, making it a strong predictor of energy consumption based on motion detection.

Through these methodical steps, this research aims to develop a robust and responsive IoT-based automatic PJU control system. By carefully designing, implementing, and validating the system, the research contributes to the advancement of smart city technologies and energy management strategies, ultimately enhancing the efficiency and responsiveness of public infrastructure, particularly in the management of energy consumption for public street lighting.

3. Result and Discussion

3.1 Results

3.1.1 Research Tools

In this final project, the research tools encompass both software and hardware components essential for operating the proposed system. The specific tools and their configurations are detailed as follows:

Table 1. Software Requirements

Software	Specification
Arduino IDE	Version 1.8.18
XAMPP	Version 8.0.30
Webserver	Apache Version 2.4.58
Database	MySQL 8.0
Data Analysis	Google Colab / Python 3.12.3

Table 2. Hardware Requirements

Hardware	Specification
ESP32	LX6 Single or Dual-Core 32-bit microprocessor with clock frequency up to 240 MHz. 520 KB SRAM, 448 KB ROM, and 16 KB RTC SRAM. Wi-Fi 802.11 b/g/n with speeds up to 150 Mbps. Supports Bluetooth Classic v4.2 and BLE. 34 programmable GPIOs. Up to 18 SAR ADC 12-bit channels and 2 DAC 8-bit channels. Serial connectivity includes 4 x SPI, 2 x I2C, 2 x I2S, 3 x UART.
Light Sensor	LDR LM393 Module
Motion Sensor	PIR HC-SR505 Module
AC PWM	AC Light Dimmer Module
Electrical Energy Sensor	PZEM-004T Module
Incandescent Lamp	Voltage = 220 volts, 40 watts
Smartphone	Minimum Android 6.0 (Marshmallow), quad-core Snapdragon 400 series processor, 2/16 GB storage, HD screen resolution (720p) or higher (capable of operating a web browser).
Laptop	Ryzen 3 3200U Processor, 16 GB of DDR4 RAM, 512 GB storage, 14” HD TN220nits Anti-Glare display.

3.1.2 Methodology Implementation

The implementation of the device involves the process of constructing a prototype for the "IoT-Based Public Street Lighting Control System Using ESP32 Microcontroller." This prototype consists of a series of hardware components, as outlined in Figure 4. The prototype is designed to be connected to the internet and operated through a web-based application.

Figure 4. Device Implementation

Figure 4 Caption:
1. ESP32 Microcontroller
2. PIR Sensor
3. LDR Sensor
4. PZEM-04T Module (voltage, current, power, energy sensor)
5. PWM Module

3.1.3 System Implementation

System implementation refers to the process of developing a web-based software application used for monitoring and remotely controlling the IoT-based public street lighting system. The software interface displays various parameters such as the light sensor value (lux), PIR sensor status, and electrical metrics related to the street lighting system, including voltage, current, power (watt), and energy consumption (kWh). In addition to monitoring, the software enables users to control the street lighting system remotely, providing an option to turn the lights on or off from a distance.

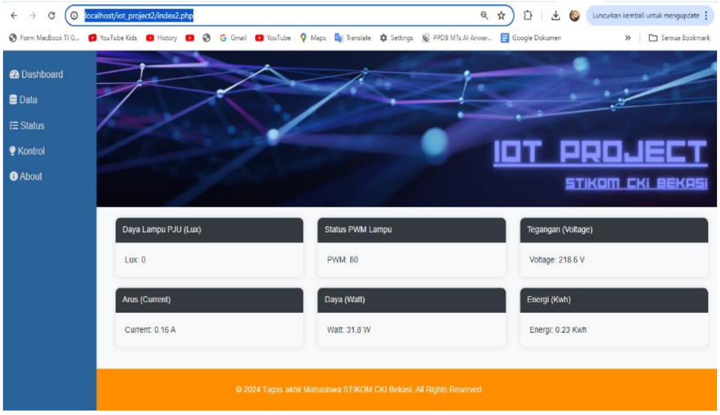

Figure 5. System Implementation (Dashboard)

3.1.4 Modeling Simple Linear Regression Data

Data modeling involves a series of steps taken to create a model for simple linear regression analysis. This process employs the least squares method, which helps in understanding and predicting the relationship between the independent variable (pir_state) and the dependent variable (watt). The model estimates the coefficients that minimize the sum of the squared errors between the predicted and actual values. The data modeling program is presented in Figure 6.

Figure 6. Simple Linear Regression Data Modeling

3.1.5 T-Test Modeling

The T-test modeling process involves the use of an Independent Two-Sample T-test. This statistical test compares the means of two independent groups of data—in this case, the watt data before and after the intervention. The Independent Two-Sample T-test is used to determine whether the mean difference between the two groups is statistically significant or merely due to chance. The data modeling program for the T-test is illustrated in Figure 7.

Figure 7. Independent Two-Sample T-Test Data Modeling

3.1.6 Data Analysis Testing

The testing of simple linear regression analysis involves running the program and evaluating the results of the test and validation within the simple linear regression model developed by the researcher. The results of this analysis are depicted in Figure 8.

```
                            OLS Regression Results
==============================================================================
Dep. Variable:                   watt   R-squared:                       0.191
Model:                            OLS   Adj. R-squared:                  0.188
Method:                 Least Squares   F-statistic:                     73.20
Date:                Sun, 07 Jul 2024   Prob (F-statistic):           5.49e-16
Time:                        03:58:10   Log-Likelihood:                -866.67
No. Observations:                 312   AIC:                             1737.
Df Residuals:                     310   BIC:                             1745.
Df Model:                           1
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const         21.1301      0.223     94.673      0.000      20.691      21.569
pir_state     13.7699      1.609      8.556      0.000      10.603      16.937
==============================================================================
Omnibus:                      273.793   Durbin-Watson:                   1.879
Prob(Omnibus):                  0.000   Jarque-Bera (JB):             7408.788
Skew:                          -3.469   Prob(JB):                         0.00
Kurtosis:                      25.842   Cond. No.                         7.28
==============================================================================

Notes:
[1] Standard Errors assume that the covariance matrix of the errors is correctly specified.
Mean Squared Error: 9.633158148684874
R-squared: 0.629307872954503
```

Figure 8. Simple Linear Regression Analysis Results

The testing of the Independent Two-Sample T-test is conducted by executing the program and evaluating the results and validation within the test model. This analysis compares the watt data before and after the installation of the motion sensor. The results of this analysis are shown in Figure 9.

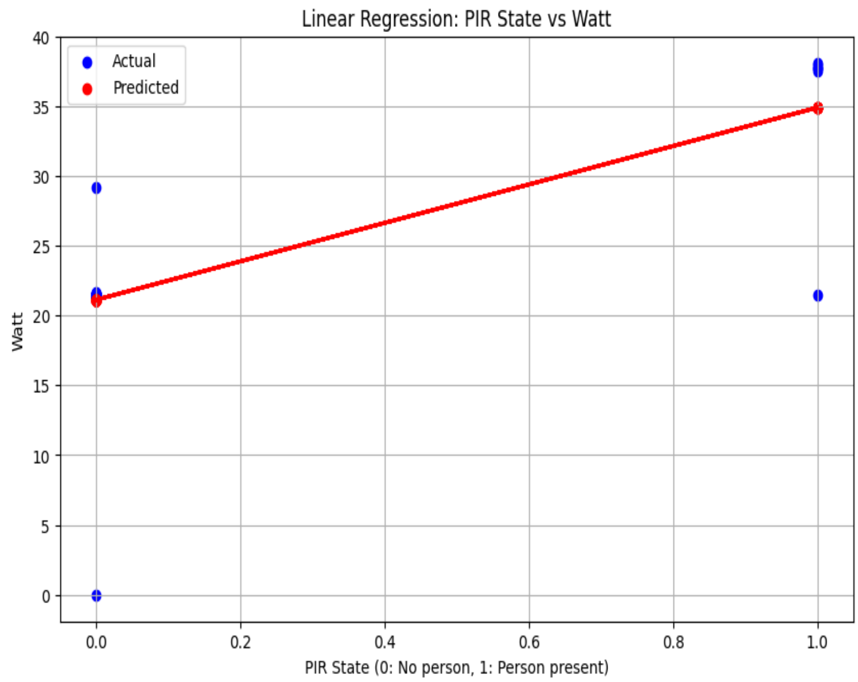

Figure 9. Independent Two-Sample T-Test Visualization

The results of the T-test, with a T-Statistic of 30.347 and a P-Value of 1.124 x 10^-116, indicate a statistically significant difference between the two sets of data tested. This significant difference confirms the effectiveness of the intervention in altering the energy consumption patterns of the street lighting system.

3.2 Discussion

The research for this project involved a comprehensive setup of both software and hardware components to develop the proposed IoT-based street lighting control system. The chosen tools and specifications were crucial for ensuring the system's functionality and performance. The software requirements, including Arduino IDE, XAMPP, Apache Webserver, MySQL, and Python for data analysis, provided a robust foundation for both system development and data handling. The hardware setup, featuring the ESP32 microcontroller, light and motion sensors, AC dimmer, and energy measurement modules, was selected to meet the technical needs of the project, ensuring effective monitoring and control of street lighting. The ESP32 microcontroller, with its high clock frequency, ample memory, and extensive GPIO options, was well-suited for handling the multiple tasks required in this system. Its support for both Wi-Fi and Bluetooth connectivity allowed for flexible communication with other devices and the internet. The integration of the LDR and PIR sensors enabled accurate measurement of light levels and motion detection, which are essential for automating street light control based on environmental conditions. The inclusion of an AC dimmer module and an energy measurement sensor ensured precise control of light intensity and monitoring of electrical consumption. The hardware implementation, as illustrated in Figure 4, involved setting up a prototype that connects various components to the internet through a web-based interface. This configuration allows for remote management and monitoring of the street lighting system. The design ensures that the system can respond to real-time data from the sensors, adjusting light levels and operational status accordingly. The software implementation, detailed in Figure 5, encompasses a web-based dashboard that provides an interface for monitoring and controlling the system. The dashboard displays real-time data from the sensors, including light levels, PIR sensor status, and electrical metrics (voltage, current, power, and energy). The ability to control the street lights remotely is a significant feature, enhancing the system's usability and flexibility.

The linear regression analysis, as shown in Figure 6, was used to model the relationship between the PIR sensor state and the power consumption (watt). This analysis is vital for understanding how sensor data influences power usage and for optimizing the control algorithms to reduce energy consumption. The regression model helps in predicting power requirements based on sensor inputs, which is crucial for efficient street lighting management. The T-Test, depicted in Figure 7, was conducted to compare the mean power consumption before and after the installation of the motion sensor. This statistical test is used to determine if there is a significant difference in power consumption due to the intervention. The results indicate a substantial difference, with a T-Statistic of 30.347 and a P-Value of 1.124 x 10^-116. This highly significant result confirms that the motion sensor has a notable impact on power consumption, validating the effectiveness of the system in reducing energy use.

The results of the simple linear regression and T-Test analyses demonstrate the effectiveness of the IoT-based street lighting control system. The regression model provided insights into the relationship between sensor data and power consumption, helping to fine-tune the system for optimal performance. The T-Test results confirmed that the installation of the motion sensor leads to a significant reduction in power usage, aligning with the project's objectives to enhance energy efficiency. The implementation of the system, including both hardware and software components, was successful in creating a functional and efficient street lighting control solution. The real-time monitoring and remote-control features of the web-based software contribute to better management and operational flexibility. The use of advanced sensors and data analysis techniques supports the system's goal of optimizing street lighting based on environmental conditions and user needs. This research highlights the potential of IoT-based systems in improving the efficiency and effectiveness of public infrastructure. The integration of sensors, microcontrollers, and web-based software provides a powerful tool for managing street lighting and other public services. Future work could focus on further refining the system, exploring additional features, and evaluating its performance in different settings to maximize its benefits.

4. Related Work

Research on smart street lighting systems based on the Internet of Things (IoT) has significantly advanced, particularly in energy efficiency and better urban management. Abdullah *et al.* (2019) developed a street lighting system that integrates sensors and controllers to adjust light intensity based on time, proving to reduce energy wastage compared to conventional street lights [11]. This aligns with the proposed research focus, which also emphasizes the importance of smart technology in improving operational efficiency and reducing energy costs. Meanwhile, Gagliardi *et al.* (2020) highlight the importance of adaptive lighting systems that use sensors and control algorithms to operate autonomously within the IoT framework. This research underscores the potential of adaptive lighting systems to enhance energy efficiency by adjusting light intensity based on environmental data [12]. This is in line with the proposed research, which also explores the effectiveness of automated IoT-based lighting systems through analytical approaches. Mary *et al.* (2018) proposed an IoT-based street lighting control system that demonstrates significant potential in reducing energy consumption and improving system responsiveness to environmental conditions [13]. This is comparable to the proposed research, which utilizes linear regression to analyze the effectiveness of automated lighting control. In contrast, Kuncicky *et al.* (2019) and Sarr *et al.* (2019) explored the use of MQTT communication protocols and LoRa WAN technology in smart lighting systems, offering effective solutions for lighting management [14][15]. This differs from the proposed research, which focuses more broadly on analyzing the overall effectiveness of automated IoT-based lighting systems without specifying particular communication protocols.

Energy efficiency in public lighting systems has been a major focus in modern lighting technology research. Bhaisare (2022) reviewed automatic lighting systems based on motion detection and LED technology, which can save energy by preventing electricity wastage when no vehicles are present [17]. This highlights the importance of sensor technology in improving energy efficiency, a key focus of the proposed research. Like Gagliardi *et al.* (2020), the proposed research also explores adaptive lighting systems that adjust light intensity based on environmental data [16][12]. Tleubayeva *et al.* (2022) demonstrated that smart lighting systems using sensors could reduce energy consumption by activating lighting only when necessary, such as when pedestrians or vehicles are detected [18]. This reflects similarities with the proposed research in using sensors for lighting optimization. Masri (2024) emphasizes the importance of integrated monitoring and control systems in public lighting management for better efficiency and responsiveness to lighting needs [19]. This aligns with the proposed research, which aims to explore automated IoT-based lighting systems that adjust lighting based on real-time sensor data.

The use of IoT and data analysis in smart systems has become increasingly relevant in the context of smart city development. IoT-based street lighting systems can collect and analyze environmental data, such as ambient light levels and traffic activity, to automatically adjust lighting intensity [20]. This is relevant to the proposed research, which also utilizes data analysis to optimize lighting systems. Data analysis from IoT systems not only helps in operational decision making but also provides strategic insights for long-term planning [21]. This is comparable to the proposed research approach, which uses data analytics to understand system performance and improve infrastructure planning. Other research also shows that data analytics allows for responsive management of environmental conditions and user needs. The proposed research builds on these principles by focusing on using linear regression to model the relationship between sensor data and power consumption. A comparison between conventional street lighting systems and IoT-based lighting control systems reveals several significant advantages. The proposed IoT-based street lighting control system not only offers better energy efficiency but also enhances management capabilities and responsiveness to environmental conditions. This system integrates advanced features, including a web-based management interface, which provides remote access and control, unlike conventional lighting systems that may lack such features.

5. Conclusion

Based on the discussion, results, and testing of the IoT-based automatic street lighting control system using the ESP32 microcontroller with linear regression analysis, several conclusions can be drawn. The linear regression analysis indicates that the integration of the motion sensor (pir_state) significantly affects power consumption. Specifically, the addition of the motion sensor led to an average reduction in power consumption of 13.77 watts. The R-squared value of 0.629 suggests that the model has a reasonably good capability to explain the variability in power consumption data. Furthermore, the comparison between data collected before and after the addition of the motion sensor shows a 42.67% improvement in energy efficiency. Additionally, the system demonstrated its effectiveness by automatically controlling street lighting based on the light sensor, and it supports real-time monitoring through web-based software accessible from both laptops and smartphones.

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