

Fault-Aware IoT-Driven Automated Street Light Control and Monitoring System

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ABSTRACT

Efficient street lighting is a key component of urban infrastructure, contributing to safety, energy conservation, and sustainable development. The advent of Internet of Things (IoT) technologies enables real-time monitoring, automated control, fault detection, and remote management of street lighting systems. This review paper critically examines recent research on IoT-based automated street light systems with integrated fault detection and reporting. Key solutions are compared in terms of architecture, sensors and communication technologies, fault detection mechanisms, energy savings, and implementation contexts. Shortcomings and future research directions are identified to guide the development of more robust, scalable, and cost-effective systems.

Keywords:- IoT, street lighting, automated control, fault detection, energy efficiency, smart city

1. INTRODUCTION

Street lighting plays an indispensable role in modern urban and rural infrastructure, contributing significantly to public safety, energy efficiency, and the overall functionality of cities. However, the traditional approach to street lighting—where lights operate on fixed schedules or require manual control—has proven inefficient, energy-intensive, and costly. In many developing regions, streetlights remain operational even during daylight hours due to faulty circuits or lack of monitoring, leading to unnecessary energy wastage. Conversely, lights may fail to operate at night because of lamp or circuit faults, compromising road safety and increasing accident risks. To overcome such inefficiencies, modern technological advancements have increasingly focused on the integration of Internet of Things (IoT) systems in urban utilities. Among these, the IoT-based Automated Street Light Control and Monitoring System has emerged as a promising innovation aimed at optimizing lighting operations while enabling fault detection and real-time reporting.

1.1 Background and Motivation

The growing global emphasis on sustainability and energy conservation has made smart street lighting an essential component of smart city infrastructure. Traditional systems typically rely on manual intervention or simple timers to control lighting, making them vulnerable to inaccuracies due to seasonal daylight variations and weather conditions. Moreover, these systems lack the capability to detect operational faults automatically, resulting in delays in maintenance and higher operational costs.

According to the International Energy Agency (IEA), public lighting accounts for up to 19% of total urban energy consumption in developing economies. Thus, integrating IoT technologies in streetlight systems is not merely a matter of convenience but a step toward achieving environmental and economic sustainability.

IoT technology allows physical devices such as sensors, microcontrollers, and communication modules to interconnect through the Internet and share real-time data. In the context of street lighting, this connectivity can automate decision-making processes—turning lights on or off based on environmental conditions, detecting faults, and sending alerts to maintenance teams. A fault-aware IoT system extends this concept further by incorporating mechanisms for anomaly detection, predictive maintenance, and automated reporting, thereby minimizing downtime and improving the reliability of public infrastructure.

1.2 Role of IoT in Street Lighting Systems

The Internet of Things enables the interconnection of distributed components within a smart lighting network, such as sensors, controllers, gateways, and cloud platforms. These components collectively form a dynamic ecosystem that monitors and controls lighting conditions based on real-time data. A typical IoT-enabled streetlight system consists of several subsystems:

- **Sensing Unit:** Includes light-dependent resistors (LDRs) for detecting ambient light levels, infrared (IR) or motion sensors for detecting pedestrian or vehicular movement, and current sensors for detecting lamp failures or power fluctuations.
 - **Control Unit:** Usually built around microcontrollers or development boards such as Arduino, ESP8266, or Raspberry Pi, this unit processes sensor data and makes control decisions based on predefined logic or AI algorithms.
 - **Communication Unit:** Facilitates data exchange using wireless communication technologies such as Wi-Fi, GSM, ZigBee, or LoRa. The system sends operational data and fault alerts to a central cloud-based server.
 - **Cloud and Data Analytics Unit:** Responsible for data storage, visualization, and predictive analysis. This layer supports dashboards for monitoring, fault detection, and energy consumption reporting.
 - **User Interface Unit:** Provides maintenance teams and city administrators with real-time status reports, alerts, and control options via mobile apps or web portals.
- By integrating these subsystems, IoT-based street lighting systems can operate autonomously, reduce energy consumption by up to 60%, and significantly lower maintenance costs through real-time fault detection and reporting.

1.3 Importance of Fault Detection and Reporting

One of the most critical features of an advanced IoT-based lighting system is fault detection and reporting. Faults in street lighting can stem from various causes, such as burned-out bulbs, short circuits, sensor malfunctions, or communication breakdowns. In conventional systems, such faults often go unnoticed until manually reported, resulting in prolonged outages. In contrast, a fault-aware IoT system continuously monitors the operational status of each lamp and associated components. Once an anomaly is detected—such as a lamp drawing no current during operational hours—the system automatically logs the fault, identifies its location, and sends alerts to the maintenance department via SMS, email, or an online dashboard.

Automated fault detection enhances operational efficiency and supports predictive maintenance by identifying patterns in failure data. For example, if certain lamps repeatedly fail in specific weather conditions or voltage ranges, the system can recommend proactive replacements or adjustments. This predictive capacity transforms maintenance from a reactive process to a proactive one, reducing both downtime and cost.

1.4 Evolution of IoT-Based Street Lighting

Over the past decade, researchers and urban planners have increasingly focused on developing intelligent street lighting solutions that leverage IoT technologies. Early systems primarily used LDR sensors and microcontrollers to automate light switching based on ambient light levels. Subsequent advancements introduced motion-based lighting, where IR sensors detect movement and trigger full illumination only when necessary, thereby conserving energy. More sophisticated systems have since emerged, featuring cloud connectivity, data analytics, and fault management modules that make the infrastructure self-diagnosing and adaptive.

In recent years, IoT integration has extended beyond automation to include machine learning algorithms for optimization and fault prediction. For instance, by analyzing historical lighting data, systems can dynamically adjust brightness levels according to traffic density, weather, or time of day. This intelligent adaptability has positioned IoT-enabled lighting systems as a core component of sustainable smart city planning.

1.5 Challenges in Existing Systems

Despite considerable progress, existing IoT-based street lighting systems still face several challenges.

- **Scalability and Network Management:** As the number of connected devices increases, maintaining efficient communication and synchronization across nodes becomes complex. Data congestion and latency can hinder real-time responsiveness.
- **Reliability and Maintenance:** Sensor drift, environmental wear, and power fluctuations can affect the accuracy of sensor readings and the reliability of fault reporting mechanisms.
- **Cybersecurity Concerns:** Unauthorized access or data tampering can disrupt operations or compromise privacy. Secure communication protocols and authentication mechanisms are necessary but often under-implemented.
- **Cost and Infrastructure Limitations:** For many rural and developing regions, high installation costs and lack of reliable Internet connectivity remain significant barriers.
- **Standardization Issues:** The absence of universal standards for IoT communication and data formats limits interoperability between devices from different manufacturers.

These challenges underscore the need for a fault-aware, efficient, and secure IoT framework that ensures continuous monitoring and fault management while maintaining affordability and scalability.

1.6 Significance of the Proposed Approach

The *Fault-Aware IoT-Driven Automated Street Light Control and Monitoring System* aims to address these challenges through a comprehensive, modular framework that combines automated control, fault detection, and predictive analytics. Unlike traditional systems that focus solely on light switching, this framework emphasizes diagnostic intelligence, enabling the system to identify, classify, and report faults in real time. Additionally, by using cloud platforms for data aggregation and machine learning-based analysis, the proposed system enhances decision-making capabilities and operational transparency.

The design principles of such a system prioritize:

- **Energy Efficiency:** By adjusting brightness dynamically and eliminating unnecessary usage.
- **Fault Resilience:** By continuously monitoring system health and detecting failures.
- **Scalability:** Through modular communication networks such as LoRa or NB-IoT.
- **Affordability:** By utilizing low-cost sensors and open-source platforms.
- **Sustainability:** By integrating renewable power sources such as solar energy for off-grid applications.

These attributes align with global initiatives such as the United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 11 (Sustainable Cities and Communities).

1.7 Research Objectives and Scope

The primary objective of this research is to review and analyze IoT-based automated street light systems that incorporate fault detection and reporting mechanisms, highlighting their design frameworks, benefits, and limitations. Specific goals include:

- To examine various IoT architectures and communication technologies used in automated street lighting systems.
- To compare fault detection techniques across existing research and identify best practices.
- To evaluate energy efficiency outcomes and maintenance performance in deployed systems.
- To propose an integrated model emphasizing fault-awareness, predictive maintenance, and sustainability.

The scope of the study encompasses urban, semi-urban, and rural contexts, recognizing that each environment presents unique infrastructural and economic challenges. By addressing these contextual differences, the research aims to propose adaptable solutions that can be implemented across diverse settings.

2. LITERATURE REVIEW

According to Chowdhury et al., the difficulty of supplying the ever-increasing demand for energy has become a severe worry for all nations. However, it is especially difficult for a third-world country like Bangladesh to find a solution to this problem. Because of the ineffective management of street lights in Bangladesh, a substantial quantity of electricity is wasted, which results in a significant annual loss of money. This is a consequence of the fact that Bangladesh is a developing nation. In spite of the fact that a big number of major studies have been conducted by researchers from other areas of the world in order to address this problem by employing the Internet of Things (IoT), very few investigations have been completed from the perspective of Bangladesh. The purpose of this research is to design an effective integrated streetlight framework that is based on the Internet of Things and provides cloud-based monitoring, control through light dimming in line with external illumination conditions and traffic detection, as well as a fault detecting system. The purpose of this investigation is to make certain that the amount of power and electricity that is consumed is kept to a minimum. We conducted an analysis of data from Chattogram City Corporation, Narayanganj City Corporation, and Dhaka North and South City Corporation, and all of the findings indicate that our proposed method has the potential to reduce the amount of money spent on energy consumption by up to approximately sixty percent in comparison to the system that is currently in place. It is possible that the most populated cities in Bangladesh might reap the benefits of implementing this creative and effective technology as part of a push to create smart cities. It is possible to put the excess electricity generated by this technology to use for a variety of applications, including some that are quite substantial, as well as for use in the house. [1]

As a result of the fact that street lights often account for between 8 and 10 percent of the total quantity of electricity that is utilized, Pappula et al. assert that the nighttime hours are particularly significant in metropolitan areas. One of the most typical methods that is utilized for the operating of this streetlight is the utilization of manual operation. The proper functioning of this streetlight is significant in its own right. The framework that we built included the incorporation of automatic street lighting that was based on the amount of sunshine that was present at the time. In addition, we made use of piezoelectric sensors in order to generate this electricity. The use of solar panels was also included. The piezoelectric sensors have the ability to transform the pressure that is produced by the movement of the presence on the road into electrical energy. This is accomplished by converting the pressure into a voltage. This technique makes it possible to both use power and put safety devices on roadways. Both of these things are made possible via the exploitation of this strategy. In addition, we were responsible for the construction of the fault detection system and its subsequent

implementation. In the current context of urbanization and technological advancement, the authors Kumar et al. say that effective resource management, particularly in connection to the usage of energy, is of the utmost relevance of the utmost importance. [2]

Within metropolitan areas, the lighting that is utilized for the purpose of street lighting is one of the most significant consumers of energy. Within the scope of this article is the presentation of a Smart Street Light Fault Detection System. Internet of Things (IoT) technology, a NodeMCU microcontroller, a Light Dependent Resistor (LDR), street lights, and the ThingSpeak are the components that are used in its construction. The NodeMCU microcontroller is utilized by the system in order to make use of the LDR sensor in order to ensure that the circumstances of the ambient light are being monitored. As a consequence of this, the system is able to make the most efficient use of energy by automatically altering the settings of the street lights to the proper levels. On top of that, it contains techniques for defect identification in order to identify any irregularities that may occur in the operation of street lights. An illustration of this would be the capability to identify abnormalities that are symptomatic of faults, such as light levels that remain constant despite changes in the environment that is surrounding the device. Through the deployment of ThingSpeak, customers are able to remotely monitor real-time LDR readings, receive notifications on defects that have been found, and carry out the subsequent actions that are required. When this is done, city officials or maintenance personnel are given access to information in a timely manner, which helps them to address problems and ensure that the infrastructure is functioning without any friction. The intelligent system provides a number of benefits, such as the capability to detect flaws in advance, the ability to control itself automatically, and the ability to save energy. This technology makes it possible to obtain large energy savings, decreased maintenance costs, and better sustainability in urban contexts. These benefits can be achieved through the use of this technology. This highlights how the technology of the Internet of Things can be employed in a practical manner to develop cities that are both more intelligent and more ecologically friendly. As a consequence of this, it demonstrates how this technology may be utilized. [3]

The researchers Nanthakumar et al. develop a full defect prediction system that includes proposed solutions, accurate position tracking, automatic real-time streetlight issue diagnosis, and an efficient maintenance schedule. For the purpose of enhancing the overall aesthetic appeal of the city as well as for the purpose of protecting the general public, the functionality of street lighting is exceptionally important. Using machine learning algorithms and the Internet of Things (IoT), our system is able to continuously monitor streetlights in real time and instantly identify any potential problems that may occur. This is made possible by the combination of these two technologies. There are sensors installed in each and every streetlight, and these sensors are able to detect any anomalies in an instant and send the information to a central control system. It is feasible to discover flaws in the system as quickly as possible thanks to this. Through the use of this technique, the amount of time that elapses between the identification of a problem and the subsequent rectification of that flaw is considerably cut down. In order to achieve this goal, it is necessary to make certain that the system is both responsive and efficient. Some of the traits that are thought to be vital include the capability of the system to provide accurate geographic information, to provide solutions for faults that are detected, and to assist maintenance personnel in discovering and resolving problems in a more expedient manner. These are just some of the qualities that are currently being deemed essential. By utilizing geographic data, maintenance operations may be directed and optimized, which in turn serves to reduce downtime and enhance overall system reliability. This is made possible through the exploitation of geographic data. This study's objective is to investigate the technological features of the sensor-based system and to demonstrate how well it performs as a reliable and uncomplicated option for regions that are striving to enhance their streetlight maintenance operations. Specifically, the study will focus on displaying how well the system functions as an alternative. [4]

The purpose of this project, as stated by Samuel et al., is to give automatic control and detection of street lights that are unable to function correctly anymore. It is possible that the project that is being given will be able to quickly record the functioning conditions of these lights without requiring any kind of manual intervention. This is a nice chance. Consequently, this results in a reduction in the amount of time and work that is required from humans in order to figure out solutions to problems. As a consequence of this, in order to find a solution to this problem, we came up with a system for the automatic identification of street lights. An example of this would be the examination of the condition of the street light late at night, which should result in a notification being sent to the appropriate staff members during the night. The fulfillment of these prerequisites is required in the event that there is a problem with a particular streetlight, as well as the location of the streetlight that has been damaged. In addition, the technology is accountable for the automatic activation and deactivation of lights, as well as the identification of whether or not the street light is turned on or off. By utilizing the LDR sensor, we will be able to automatically turn on and off the street lights in accordance with the current weather conditions that are in effect. The project's objective is to enable autonomous operation of the on/off switch for street lights and to identify any failures that may occur. Additionally, the project will detect any potential problems that may

arise. It is one of the goals of the project to build a lighting system that is not only economical but also self-sufficient and efficient in terms of the amount of energy that it consumes. Furthermore, problems that occur with the illumination of streets can be fixed if they are brought to light. Either a computer located at the control station can be utilized to turn the street light on and off, or light sensors installed on the pole that supports the street light can be utilized to turn it on and off automatically. Both the lamps' durability and their performance will be enhanced if this is done. The combination of light-emitting diode (LED) bulbs with a wireless internet connection (5) can result in the creation of street lighting systems that are not only adaptive but also extremely responsive, reliable, and efficient in terms of energy consumption. [5]

3. FRAMEWORK ELEMENTS AND COMPARATIVE DESIGN

To structure future systems, a set of critical components can be identified and compared:

3.1 Sensing & Control Layer

Core sensors: Light dependent resistors (LDRs) for ambient light; IR or ultrasonic for motion detection; current sensors for fault detection. Most systems (Pappula et al., 2022; Kumar et al., 2021) adopt LDR + IR. More advanced works add current sensing or GPS location for fault location (e.g., Nanthakumar et al., 2024).

3.2 Communication & Data Layer

WiFi (ESP/NodeMCU) is common in small setups, GSM for remote areas, LoRa/NB-IoT for wide coverage. Data is transmitted to cloud platforms (ThingSpeak, AWS IoT) and dashboards for monitoring (Kumar & Vadivel, 2024). Scalability and network reliability remain open issues.

3.3 Fault Detection & Alerting Mechanism

Fault detection algorithms range from threshold checks (lamp remains ON in daylight) to predictive analytics using historical data (Chowdhury et al., 2022). Fault alerts are issued via mobile/GSM, cloud dashboards, or maintenance tickets.

3.4 Automation & Control Strategy

Quiet mode dimming, motion-based full illumination, and ambient light-based switching are common. Some systems integrate solar or piezoelectric energy (Pappula et al., 2022) which expands application in rural/off-grid contexts.

3.5 Maintenance & Reporting Interface

User interfaces, mobile apps, dashboards, and maintenance reports provide actionable insights. Real-time fault location and remote override capability are increasingly present.

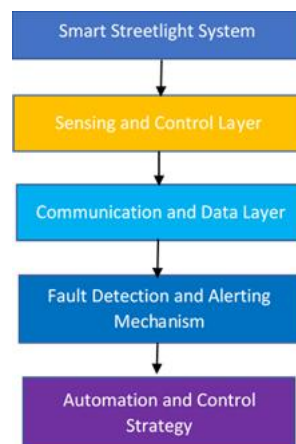


Fig. 1 Flowchart of the proposed system

4. SYNTHESIS AND GAP IDENTIFICATION

Based on the comparative review, future work could explore:

- Implementation of edge-computing nodes that perform fault detection locally and reduce cloud load.
- Use of machine learning/predictive maintenance for pre-emptive fault detection rather than reactive alerts.
- Integration of energy harvesting (solar, piezo) for self-sustaining rural street lights.
- Development of standard IoT frameworks and open data architectures for smart lighting interoperability.
- Field trials in rural and low-resource settings to assess cost-benefit, reliability, and maintenance overhead at scale.

5. CONCLUSIONS

This review presented an overview and comparison of current research on IoT-driven automated street light control systems with fault detection and reporting. While many solutions demonstrate energy savings and improved maintenance efficiency, limitations in fault coverage, scalability, cost, and standardisation remain. The proposed Fault-Aware IoT-Driven Automated Street Light Control and Monitoring System aims to guide future research toward more resilient, cost-effective, and large-scale deployments, especially for rural and smart city applications.

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