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Intelligent Street Lighting: An IoT-based System for Adaptive Brightness and Fault Management

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Abstract

The research aims to develop an intelligent fault detection and control system for street lights using an STM32 microcontroller and Internet of Things (IoT) technologies. The system uses various sensors and communication methods to manage lighting more effectively and maintain infrastructure better. Light-Dependent Resistors (LDRs), which turn lights on automatically at nightfall and off at dawn, are essential to the system's operation. Moreover, motion is detected by the infrared (IR) sensors on the street, allowing the lighting to save energy by dimming during times of low traffic and brightening when movement is detected. By using control logic and sensor readings, a relay functions as an electronically controlled switch to turn the lights on and off. To process sensor data, the STM32 microcontroller is used in the main functionality. Energy savings are facilitated by the automated on/off switching based on ambient light levels, enabled by the LDR sensor data. In addition, the device includes a GPS module for precise street light location tracking. An IoT platform transmits this location data as well as operational status and real-time sensor readings. Maintenance staff can access regional data on light quality and sensor readings through an LCD display. This extensive data enables maintenance team to focus better, use resources efficiently, and enable remote monitoring and fault identification (e.g., burned-out bulbs). This Internet-of-Things (IoT)

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system provides an economical and environmentally friendly approach to efficient street light management by integrating automation, remote control, and real-time monitoring.

Keywords: IoT (Internet-of-Things), Adaptive lighting, Fault detection, Real-time data, LDR (Light-Dependent Resistor), Street lighting Automation, IR sensor (Infrared sensor), GPS module.

1. Introduction

Global urbanisation is accelerating the need for creative solutions to handle resources responsibly and effectively. One important area for optimisation is street lighting, which is an essential part of urban infrastructure. Conventional street light systems often operate on fixed schedules, resulting in unnecessary energy consumption during periods of low traffic. In addition, it might take a lot of time and resources to diagnose and fix problems like burned-out bulbs[1-3].

Building smart cities has become increasingly popular worldwide as a way to enhance people's quality of life and mitigate the adverse environmental impacts of urbanization. In many cases, conventional street lighting management methods are expensive, and inefficient. Street lights are typically programmed to switch on and off at predetermined intervals, regardless of whether they are needed[4-7]. This leads to unnecessary energy use thus increased costs for cities. Street lights are necessary to guarantee security and safety at night. However, large light networks can be challenging to maintain, as broken lights often go unnoticed for a very long period. This can lead to energy waste, safety hazards, and increased maintenance costs. This study proposes a novel approach that uses GPS and technology for sensors to identify faults in street light[8-12]].

This proposed method uses the energy provided by the Internet-of-things (IoT) to suggest an innovative way to regulate street lights. To provide intelligent control and problem detection, this system combines a collection of sensors, communication protocols, and remote monitoring capabilities. The system may automate light level adjustments and initiate maintenance warnings by utilising real-time sensor readings and environmental data. This promotes a more economical and environmentally friendly strategy for urban lighting[13-16].

1.1 Challenges

Conventional streetlights have a set on/off schedule and often waste energy by remaining lit on deserted streets after hours. Furthermore, troubleshooting and correcting issues such as burned-out bulbs can be an inefficient and time consuming. This inadequacy results in:

- Significant power consumption: Fixed-schedule illumination wastes energy by not accounting for variations in the surrounding environment or human presence.
- Higher maintenance costs: Manual defect detection frequently requires monitoring whole networks, which causes fixes to be delayed.
- Decreased safety: Broken lights might result in areas with poor lighting and present a safety risk.

The goal of the research is to automate street light control systems and make a significant impact on public services and urban landscapes.

2. Related Work

The intelligent management of street lights, energy usage and street illumination can be optimised throughout the late hours during the night. Because, LED street illumination systems use less power than incandescent street lights, they are becoming more and more popular. Another advantage is that LED intensity is easily controllable. As a result, building movement-sensing-based street light management systems is straightforward [1]. These studies demonstrate how putting intelligent control systems in place can result in significant energy savings.

This study suggests a smart system to control street lighting and save energy. It is intended to monitor an automobile's motions on the roadway and turn on a row of street lights directly in front of the vehicle. As the automobile passes, the device turns off the tail lights. The intensity of the light will also be controlled by the technology. Consequently, sustainable street lighting is maintained with minimal usage of electricity [2].

This study describes an automated street light solution that adjusts intensity based on weather, vehicle motion, and other environmental variables using wireless sensor networks [3] method and LEDs. Based on variations in the seasons, the system automatically modifies the street illumination. Additionally, it features a time-dependent auto loop mechanism for when a car crosses the street. It will significantly impact the use of less energy. The main objective of research [4] is to develop an energy-efficient street lighting scheme that automatically switches on and off based on the quantity of cars inside its specified areas. The research also exposes the limitations connected with previous methods. Because to this work's effectiveness and efficacy, the electricity usage is reduced by 80.34%, lighting quality is enhanced, and the product's lifespan of LED is increased.

An Internet of Things-based system for real-time street light health monitoring is proposed in the study [5], enabling quick diagnosis and repair of malfunctioning fixtures. This research presents a system for sensing light intensity and tracking the position of street lighting. Measurement data will help enhance street lighting performance and increase the effectiveness of maintenance tasks.

The proposed method aims to devise an intelligent IoT-based street light system that includes fault detection and energy conservation. By utilizing reliable wireless sensor networks and real-time data processing, this method seeks to provide an affordable and scalable approach to intelligent street light control.

3. Proposed Methodology

This research uses the capabilities of the STM32 microcontroller, a variety of sensors, and communication protocols inside an Internet of Things framework to present an innovative method to street light control and fault detection. The proposed smart street lighting management and fault detection system makes use of IoT-enabled real-time communication, controller logic execution, and sensor data processing.

The block diagram of the proposed approach is shown in Figure.1 which is made up of a network of connected parts that include IR sensors, LDR module, GPS module, relay, street light,, 16*2 LCD , power supply and IoT Module to manage street lights intelligently.

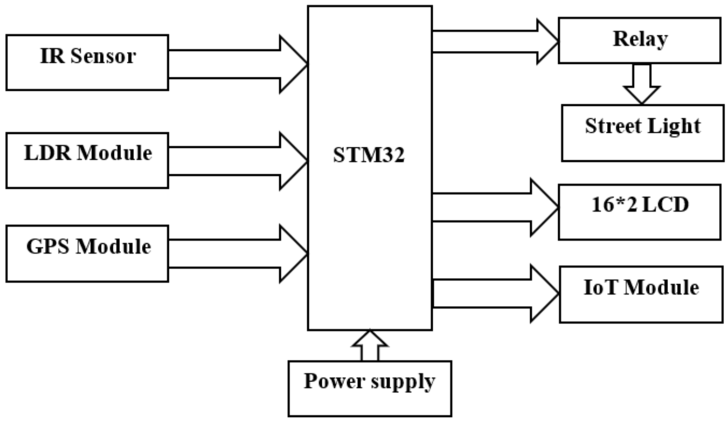

Figure 1. Proposed Block Diagram

3.1 Sensor Data Acquisition

An STM32 microcontroller was chosen for its processing power, low power consumption, and accessible programming tools. It manages sensor data collection, control logic, and hub-to-hub communication. The ambient light levels are continuously measured by the LDR sensor. Low light levels or darkness cause the LDR to have high resistance. On the other hand, in bright lighting circumstances (high lighting intensity), the resistance of the LDR dramatically drops. The IR sensor detects movement on the roadway for motion detection. Low traffic conditions are indicated when there is no motion detected. On the other hand, when motion is detected, it indicates the presence of a vehicle or pedestrian. Similar to location awareness, the street light's exact coordinates are found by the GPS module. Geotagging sensor data enables making location-specific control decisions on this information.

In this instance, the relay functions as a managed switch, turning on and off the street light in response to control logic and sensor readings. The microprocessor, which in turn controls the functions of all other parts and sensors, receives constant electricity from the power supply. At every street light node, the LCD serves like a local user interface, providing technicians with basic data and status updates. The LCD displays information on the screen after receiving data from the microcontroller.

3.2 Data Processing and Control Logic

The main processing unit of every street light node is the Microcontroller Unit (MCU). It gathers information from the GPS module, IR sensor, and LDR. The MCU evaluates the sensor data using preprogrammed control logic This logic considers factors such as the predetermined schedule based on sunrise and sunset times (collected through GPS data), real-time ambient light conditions (provided by the LDR readings), and the presence of vehicles or pedestrians (indicated by data from the IR sensor)..

The MCU decides the appropriate action based on the schedule and LDR readings: When the MCU detects darkness and determines it is evening (as per the schedule), it activates the relay to turn on the street light. Alternatively, the MCU deactivates the relay to turn off the street light if it is daytime (according to the schedule) and the LDR readings confirm sufficient ambient light.

If the IR sensor does not detect movement for a predefined period, the MCU interprets it as low traffic. To minimize energy consumption, the control logic may instruct the MCU to dim the street light. When the IR sensor detects motion, the MCU increases the light intensity to ensure adequate lighting for security and safety purposes.

3.3 Communication and Centralized Management

The street light nodes and the central hub of the system exchange data in an effective and dependable manner using an Internet of Things communication protocol called MQTT (Message Queuing Telemetry Transport). A lightweight publish/subscribe messaging pattern is provided by MQTT, which reduces data transmission and maximises network bandwidth utilisation. The ambient light levels are continually monitored by the LDR sensor. The street light's relay is automatically turned on and off by the microcontroller utilising pre-programmed dawn and sunset timings (obtained via the GPS module). When motion is detected by the IR sensor at night, the microcontroller uses the relay to adjust the light intensity. It increases the light intensity in response to movement and decreases it during periods of low traffic.

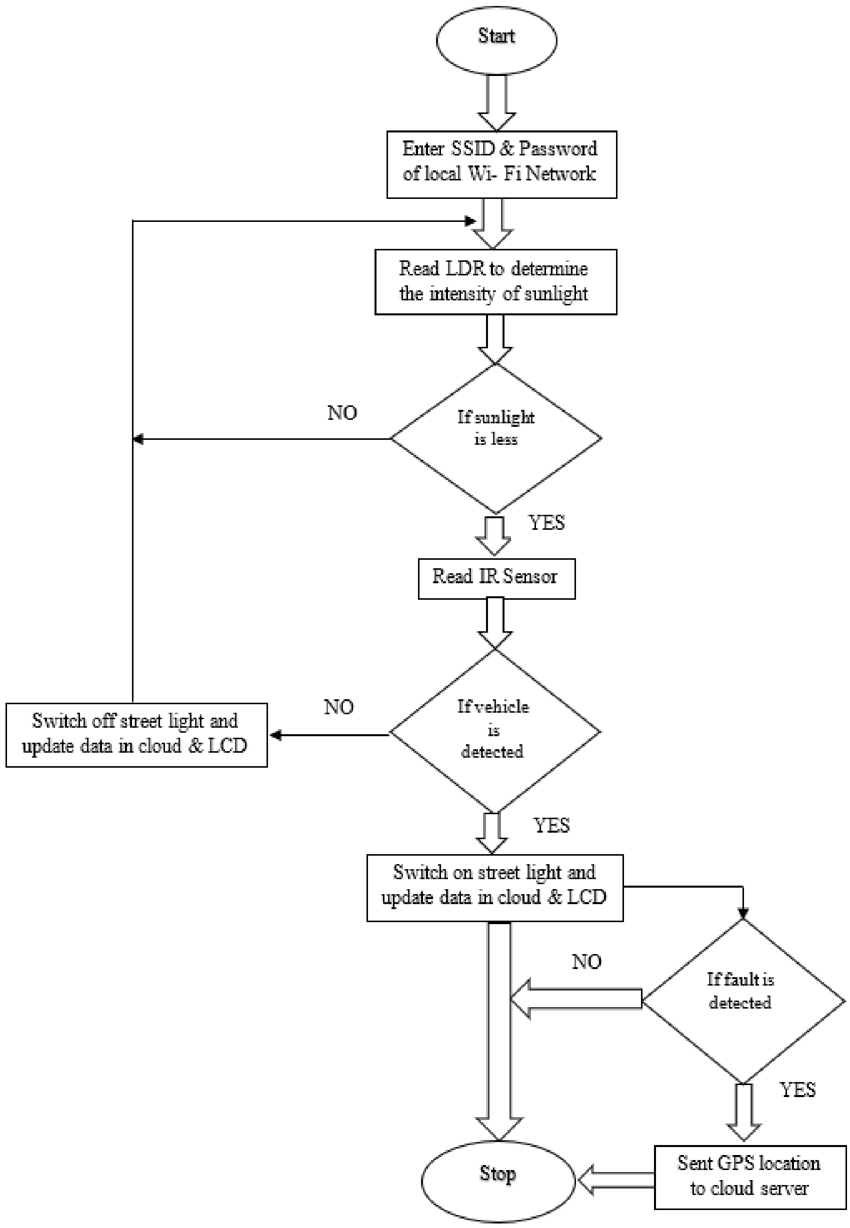

Figure 2. Flowchart Diagram

The above Figure .2 shows the flowchart for this proposed street light. For Real-time Data Transmission, the GPS module, IR sensor, and LDR (light level) all provide data to the microcontroller. The communication module is used to send this merged data packet to the central hub. All street light nodes send data to the central hub, which collects and analyses it based on predetermined data stored (seasonal variations in light conditions), pre-programmed schedules (such as brighter lights during peak hours), motion detection events, and real-time light levels. Using the communication module, the central hub modifies the light intensity level of each street light node by generating control instructions based on this analysis.

The central hub continuously monitors sensor data and system health metrics to detect any unusual activity. The system identifies failure at a specific node if there is a significant deviation from predicted measurements. (e.g., abrupt reduction in light level suggesting a burnt-out bulb). The system sends out an alarm notice to maintenance staff, giving them specifics about the suspected fault's location (as determined by GPS data). Here Table 1 and Table 2 shows the hardware and software components which are used for this project.

Table 1. List of Hardware Components

S. No.	Hardware Tools	Function
1	STM32 Microcontroller (MCU)	It interacts with the central hub to transmit and receive commands, interpret data from LDR and IR sensors, and operate the relay to turn on and off the street light. Basic information, such as the condition of the light, is displayed on the LCD.
2	LDR (GL5528)	It monitors ambient light levels day and night and, in the event of an enormous change in light levels, initiates data transfer to the central hub.
3	IR Sensor (HC-SR501)	It uses pre-programmed circuitry to detect movements on the roadway, which then initiates data transfer and possible light changes.
4	Relay (SRD-05VDC-SL-C)	It functions as a programmable switch, using orders from the MCU to turn on and off the street light.
5	GPS Module (NEO-6M)	It pinpoints the precise spot of the street light node and enables geotagging of data provided to the central hub for effective control and upkeep.
6	LCD Display (16x2)	To provide maintenance staff access to local information, such as the current light level.
7	ESP32(IOT Module)	An intelligent street light's brain is an Internet of Things (IoT) module, which gathers and transmits data from sensors (light, motion, and position) for management and monitoring.

Table 2. List of Software used

S. No.	Software Tools	Description
1	Arduino IDE	This open-source software environment offers code creation, compilation, and uploading capabilities.
2	Language – Embedded C	The data collection, processing, actuation, and controls are managed by embedded C code developed using necessary libraries.

4. Result and Discussion

In contrast to conventional street lighting systems, as shown in Figure.3 the system achieves significant energy consumption reductions by utilising autonomous light management based on real-time parameters (motion, ambient light). At night, as shown in Figure 4 if motion is present, the light intensity increases for better visibility. The STM32 microcontroller checks the LDR sensor (Figure 5) to determine light level. When there is more traffic, adaptive light intensity makes sure there is enough light, which improves safety for both drivers and pedestrians.

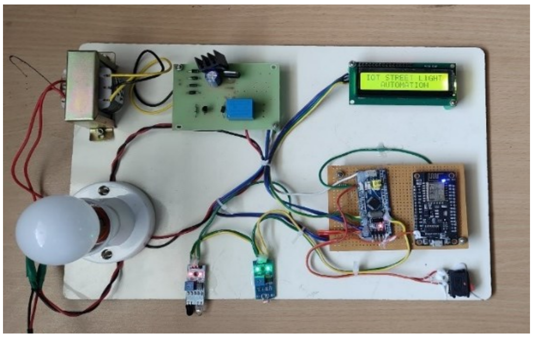

Figure 3. Hardware Prototype

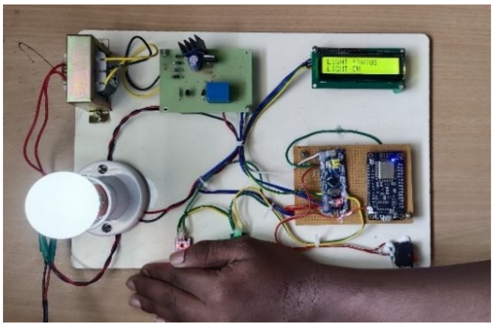

Figure 4. Light ON Condition when IR Detected

Continuously, the STM32 microcontroller gathers data of the light level, motion, GPS location and transmits it to a central hub using an IoT module. The central hub receives data from all street lights, analyzes it for potential faults and optimizes light intensity based on real-time conditions of motion detection and scheduled timing. If needed, the hub sends control commands to adjust light intensity at specific street lights. Also, it triggers fault alerts for maintenance crews if potential faults are detected as shown in Figure.6. The LCD display shows the current light status (on/off, Fault detected) shown in Figure 6 for maintenance personnel on-site.

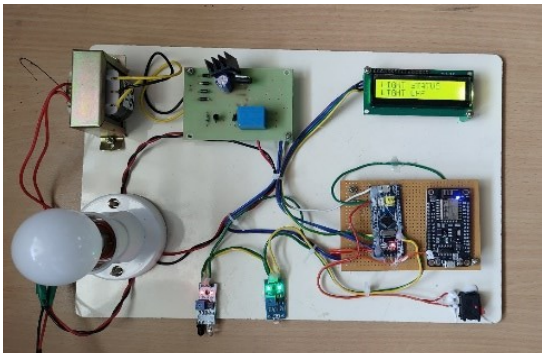

Figure 5. Light Off Condition

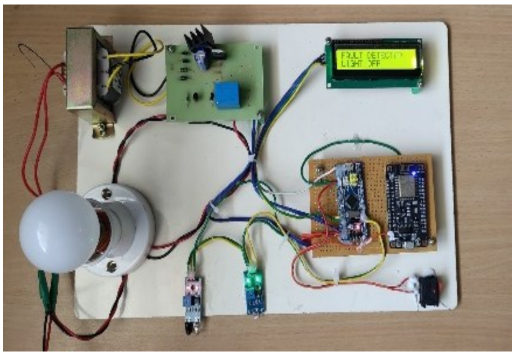

Figure 6. Fault Detected

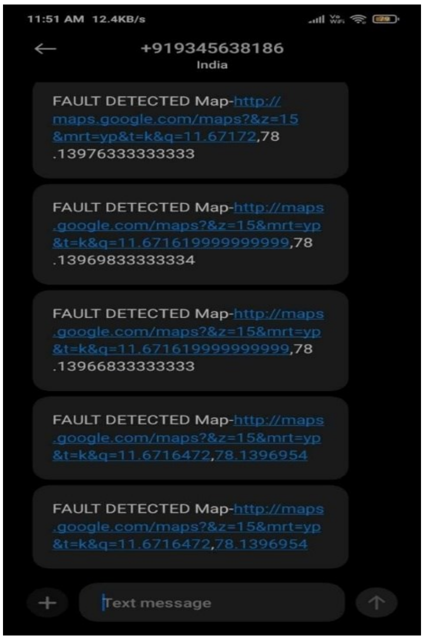

Figure 7. Fault Notification with GPS Location

The GPS module continuously determines the precise location of the street light. This location data is then correlated with sensor readings such as light levels and motion detected by the LDR and IR sensors. When this combined data (sensor readings + location) is transmitted to the central hub, it enables quick identification of faults in sensor data from specific street lights. The GPS information (Figure 7) helps pinpoint the exact location for maintenance crews to be dispatched efficiently.

5. Conclusion

This research uses Internet-of-Things (IoT) concepts to create an intelligent fault detection and control system for street lights. A network of street light nodes, each containing an SMT32 microcontroller for central processing, is used in the proposed system. These nodes incorporate GPS modules for exact position tracking, LCD displays for local status updates, relays for light control based on system commands, IR sensors for motion detection, LDR sensors for ambient light levels, and GPS modules for accurate location tracking. The SMT32 microcontrollers gather real-time sensor data, which the system uses to regulate light intensity dynamically. When compared to conventional street lighting, this results in considerable energy savings since light levels are dynamically adjusted based on real-time conditions like darkness and motion detection. Furthermore, the central hub's geo-tagged fault detection is made possible by the incorporation of GPS modules. This facilitates the timely detection and fixing of broken lighting fixtures, enhancing maintenance procedures and reducing downtime.

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