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Original Article

Analysis of System Response, Energy Savings, and Fault Detection in a Weather and Traffic-Adaptive Smart Lighting System

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Abstract - *In the era of smart lighting systems, it is essential to save energy without sacrificing the quality of light. The main aim of this research work is to develop a wireless LED street lighting system that incorporates smart control techniques to maintain appropriate light levels over street surfaces in response to variations in object speed and to improve visibility during foggy conditions. In this control scheme, the main microcontroller senses the daylight level and collects data on fog from a third-party weather API. If fog is detected, the system adjusts the LEDs from cool white to warm white to improve visibility. Additionally, the system detects the presence of objects or pedestrians; if an object is present, it increases brightness depending on the speed of the object up to 100% of LED light. Otherwise, it reduces the LED brightness to 25%. The system also includes fault detection by monitoring the lamp voltage and current to determine if any LED light is faulty, providing timely maintenance alerts. This smart control system ensures energy efficiency and optimal lighting conditions, adapting dynamically to both environmental and situational changes, thereby enhancing safety and visibility on the streets.*

Keywords - *Energy efficient, Fault detection, Streetlight, Traffic adaptive, Weather adaptive, XBee.*

1. Introduction

Traffic accidents during foggy weather are a common problem in street lighting systems [1]. Studies have shown that suitable light levels can enhance visibility on street surfaces, potentially reducing traffic accidents. This can be achieved by introducing appropriate light levels during traffic flow using smart control techniques. Surveys indicate that streetlights consume a significant amount of electrical energy, highlighting the need to reduce this consumption. The goal of this work is to implement an energy-efficient lighting system that improves visual performance on street surfaces at night, reduces traffic accidents, maintains proper traffic flow, and enhances the safety of pedestrians, cyclists, and drivers [2].

The use of LED lamps for street lighting has increased significantly. LED-based streetlight technology offers several advantages, including greater energy efficiency and higher luminous intensity compared to other light sources like SON and SOX lamps. Additionally, LED lamps are eco-friendly due to their low energy consumption. The Correlated Color Temperature (CCT) of LED lamps can be varied and adjusted, and their high Color Rendering Index (CRI) enhances visual performance during normal weather. In adverse weather conditions, the visual performance of users identifies the type of object, its direction of movement, and its speed, which helps to reduce the number of accidents that often happen on street surfaces.

For the development of a smart city, it is necessary to make the LED street lighting system smarter by implementing a web-based system to enhance energy savings. Additionally, using energy-efficient electronic sensors and integrating wireless network modules like XBee [2, 3] and LORA protocols is crucial. The focus of this article is on the use of weather-dependent, human-responsive, CCT-based smart LEDs for street surfaces [2, 4, 5].

Smart lighting systems can be either cloud-based or sensor-based, each with its advantages and disadvantages. The advantage of a cloud-based approach is that it does not require additional sensors to detect objects, relying instead on cloud-dependent data, which can sometimes be incomplete or inaccurate regarding traffic information. In contrast, a sensor-based smart lighting approach uses intelligent control of streetlights based on real-time traffic information extracted by object detection sensors connected to a microcontroller.

Although the sensor-based approach requires additional sensors, which can increase the overall cost of streetlights, it offers the benefit of providing accurate and real-time data. From the perspectives of energy savings and user experience, the sensor-based smart lighting system is more realistic and effective than the cloud-based approach. Consequently, it is preferred by researchers for its ability to deliver precise, real-time data and improve overall system performance.

The aim of using a sensor-based smart lighting approach is to dim streetlights according to the presence and speed of traffic. Therefore, accurate measurement of traffic speed and detection is a key factor in designing smart lighting systems. Both cloud-based and sensor-based [2, 6] approaches rely on IoT technology, utilizing wireless technologies such as LoRa, ZigBee, GSM, and NB-IoT [7-9].

Among these, ZigBee technology is most favored, primarily for security reasons. Among the existing research, the problem is that no literature provides integrated solutions for both traffic-adaptive and weather-adaptive features that can be implemented in a single lighting system. Because for proper visibility during foggy weather and saving energy to reduce running costs are the most important factors for the street lighting system.

2. Related Works

For performing this research work several literature related to smart lighting systems and LED color changing have been studied [4-5, 10]. In retrospect, the authors proposed several works on LED street lighting systems based on wired and wireless technology, such as ZigBee and IoT. The control approaches differ in these proposed schemes. Wired systems face challenges such as high cable installation costs, connection complexity, and high maintenance costs. However, wireless network systems offer advantages like low installation costs, scalability, ease of installation, and self-healing capabilities. DALI is well known for controlling LED streetlights, and many researchers have proposed various control schemes for dimming streetlights. However, DALI has disadvantages, including high latency for dimming and a slow response time to control signals. In a study by Jiang et al. [8], the authors proposed an object speed-based detection strategy using a doppler radar sensor to detect objects. Based on the detection speed, the microcontroller adjusts the brightness of LED streetlights. This scheme is more energy-efficient compared to conventional lighting systems.

Other literature discusses different smart lighting concepts but generally lacks information on adaptive schemes. In a piece of literature by Daely et al. [2], the authors suggested using two LED fixtures on the same lighting pole, which requires more equipment to switch between the two LED luminaires. According to this control scheme, each pole has policies for enhancing visibility in foggy weather, which increases installation and running costs. In that study, when the microcontroller detects foggy weather, it switches the LEDs from 5000K to 3000K, and when the weather is clear, it switches from 3000K to 5000K. A comparative study of designed and existing lighting systems is shown in Table 1.

According to another literature by Chen et al. [9], using IoT technology data is transmitted by NB-IoT communication network system to the microcontroller to tune LED as per requirement. Based on the existing literature, authors have separately provided solutions to improve visibility in foggy weather and to save energy during nighttime over street surfaces. A research gap has been identified in developing a lighting system that can simultaneously provide fog-penetrating lighting, minimize the number of lighting units used, and implement a dynamic speed-based lighting control strategy.

Table 1. Comparative study of designed lighting system with existing lighting systems

Comparison Attribute	Designed System	Existing Lighting Systems
Number of streetlights over each pole	Single LED light over each streetlight pole	Two LED lights over each pole considered in the literature
Real-time quick, responsive, weather-dependent	Quick responsive	Take some time
Weather API dependant	Yes	Yes
Traffic accident reduction feature	Considered changing the color of RGB LED CCT on demand from 6500K and 3000K and vice versa.	Considered using two LED arrays with CCT of 3000K and 5000K
Weather factor consideration	Considered	Considered in one literature
LED streetlight control type	XBee based control	TCP/IP protocol and DALI protocol
Weather Sensor	Considered two sensors connected to the main microcontroller	Considered four sensors in each streetlight pole only for weather data
Wireless communication consideration among streetlights	Considered	Considered

Additionally, to design such a system that helps reduce the speed of rash drivers to prevent accidents in both normal and foggy weather conditions and aid in identifying faulty lighting systems on street surfaces. Based on existing lighting research [2, 4-5, 7-16], this architecture utilizes multiple sensors, such as the LDR sensor, DHT11 sensor, and RCWL0516 sensors, as inputs for the microcontroller. These sensors generate input signals for brightness control and CCT adjustment suitable for the current weather conditions.

A detailed description of the designed scheme is provided in Section 3.

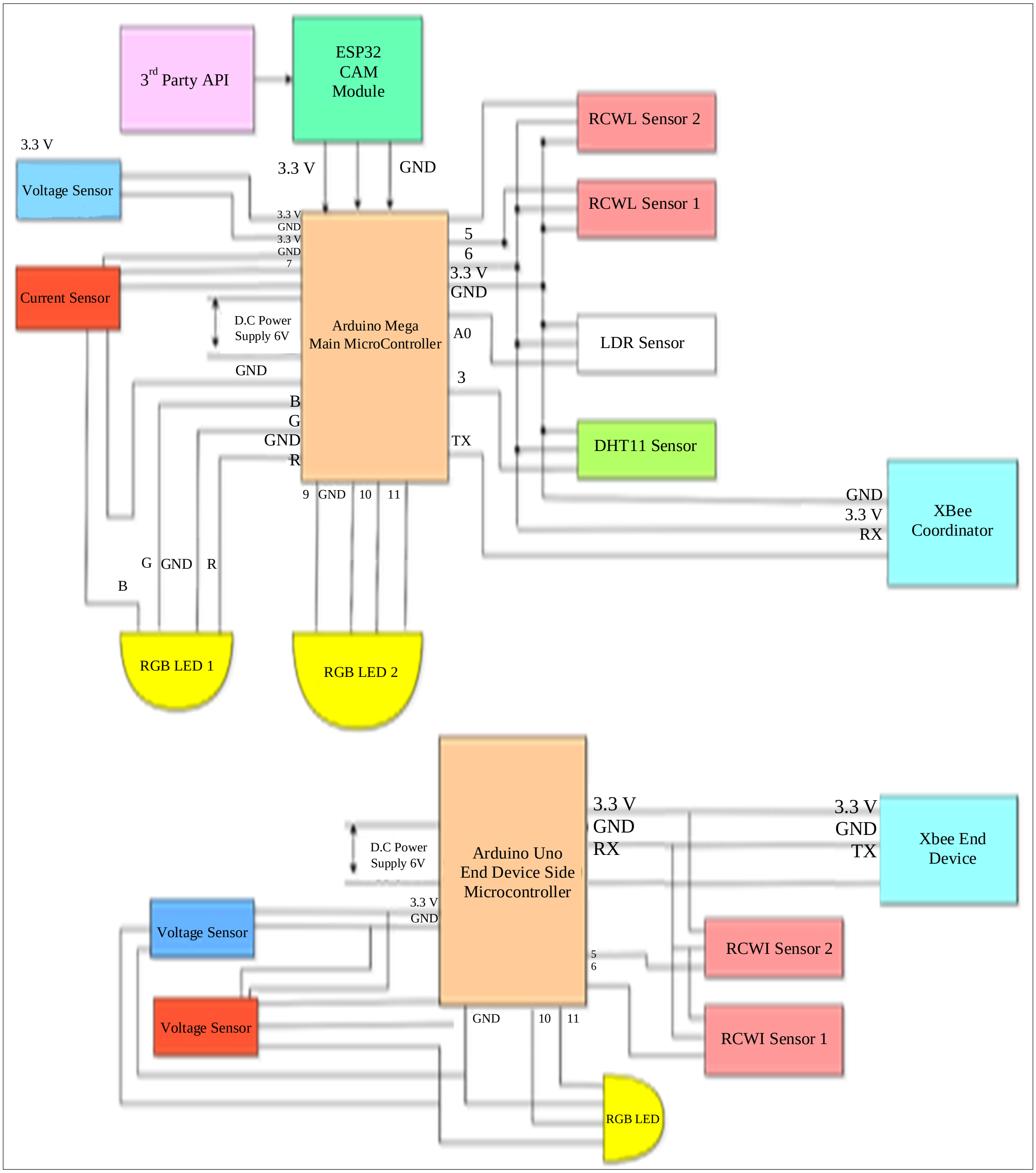

Fig. 1 Block diagram of designed lighting system

3. Designed Street Lighting System

3.1. Features

a. One novel feature of the designed system is that it offers both weather-responsive and traffic-responsive attributes based on input sensor values. The microcontroller automatically adjusts the CCT and brightness of the LED light.

b. Another novel feature of this system is that it uses only one LED light per pole and adjusts its brightness, replacing the existing two LED fixtures on each streetlight pole [2].

c. The scheme provides a way to identify faulty streetlight poles and helps reduce high-speed traffic by sending messages to drivers to control their speed.

d. This system is energy-efficient, using one RGB LED instead of two LEDs per streetlight pole and reducing the number of sensors compared to existing designs. The proposed scheme uses fewer sensors at the XBee coordinator-linked streetlight pole, whereas existing designs use more sensors per pole, making the design more cost-effective and energy-saving.

e. The designed scheme is not fully IoT-based, ensuring that the security of the lighting system is encrypted. This prevents outsiders from controlling the system and disrupting its AI-based functionality.

f. The designed scheme is more responsive compared to existing systems. When the XBee coordinator-linked the microcontroller senses a need to change the CCT [2] of the LED lights; it instantly sends instructions to the XBee-linked other streetlights to adjust the CCT.

This system adjusts the CCT of LED streetlights over shorter distances compared to existing lighting systems, making it more responsive to real-time weather conditions. Since fog density can vary within short ranges, visibility conditions may change, and for that reason fully IoT-based system cannot become fully effective.

Figure 1 shows the block diagram of the designed lighting system comprises one Arduino Mega and one Arduino Uno microcontroller, a DHT11 sensor, an LDR sensor, two RCWL0516 sensors, and two XBee wireless communication modules. The Arduino Uno features an 8-bit ATmega328P microcontroller, 14 digital I/O pins, 6 analog pins, a voltage regulator, a reset button, and USB connectivity. The DHT11 sensor measures the humidity and temperature of the environment, while the LDR sensor measures the lighting conditions of the street.

The RCWL0516 radar sensors detect object presence on the street surface within their detection range and identify the speed of moving objects. The system includes three XBee S2C modules to send and receive control signals between streetlights wirelessly. XBee modules can operate in either AT mode or API mode, with this scheme utilizing AT command mode for signal transmission and reception. Proper XBee configuration is essential for the modules to function correctly.

The XBee S2C modules can establish secure wireless coverage up to 4,000 feet in an outdoor environment, enabling the creation of an XBee network with modules set as coordinators, routers, and end devices. Each streetlight is directly connected to an XBee module via Tx/Rx pins to transmit and receive signals for updating the operation of the LED streetlights.

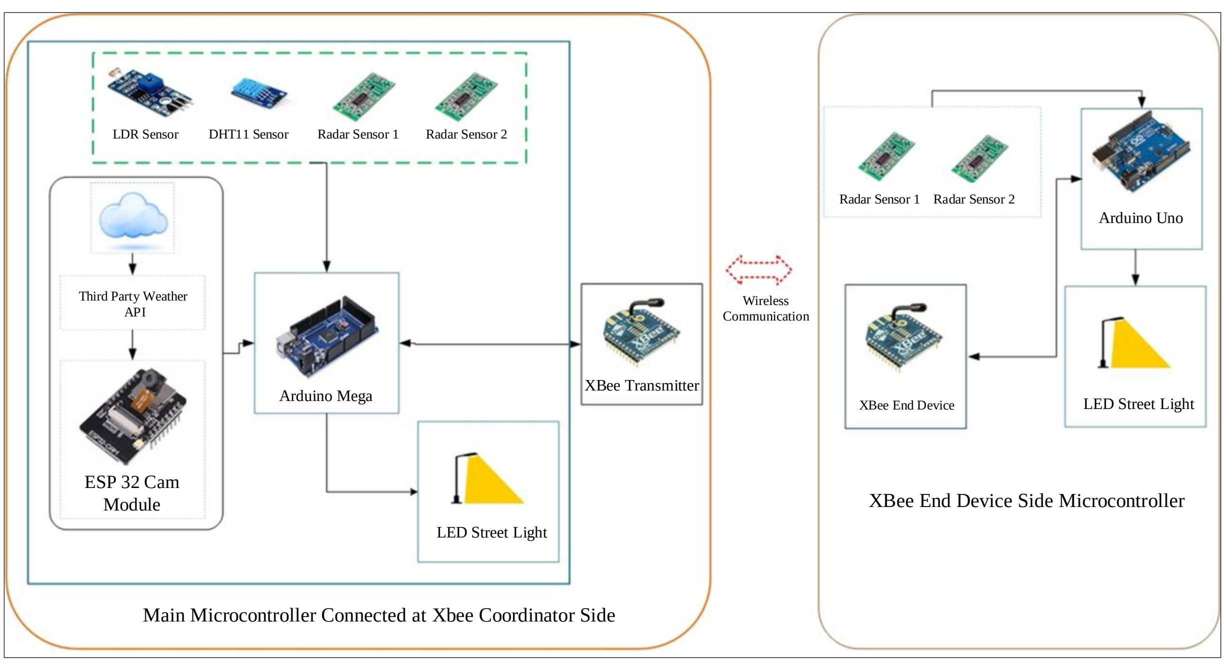

Fig. 2 Functional diagram of designed lighting system

3.2. XBee-Based Streetlight Communication

In this designed scheme, the main microcontroller initially generates a control signal depending on the input sensor values and sends it to other streetlights via the XBee coordinator. Other streetlights receive the transmitted signal from the coordinator and update their LED functions accordingly using the XBee communication protocol. One Arduino Uno serves as the main microcontroller, while the LDR sensor, DHT11 sensor, and two RCWL0516 sensors provide essential environmental information and object detection values. Depending on the input values and control logic, the main microcontroller generates a control signal for pedestrian and driver visibility, updating the operation of its connected LED and transmitting the same signal via XBee to other LED streetlights.

In this prototype model, one Arduino Mega acts as the main controller connected to an LDR sensor, a DHT11 sensor, and two RCWL0516 radar sensors. The main microcontroller serves as a transmitter, sending control signals to receiving microcontrollers placed on two sides of the main microcontroller. These receiving microcontrollers are configured in the same channel and PAN ID. Depending on the programming, the main microcontroller identifies object movement and weather conditions, adjusting the LED lights' operating conditions accordingly.

Two RCWL0516 radar sensors on the main microcontroller side detect object movement in opposite directions on the street. To verify the model's functionality, an object is moved from radar sensor 1 to radar sensor 2 direction. The main microcontroller senses the movement and increases the brightness of the LED streetlight connected in the direction of the object's movement. It also generates a control signal sent to one of the receiving microcontrollers on the same side as radar sensor 2. Similarly, when an object moves from radar sensor 2 to radar sensor 1, the brightness of the LED increases to full brightness.

The control scheme adjusts the LED brightness based on the speed of moving objects, with brightness levels set at 100%, 75%, 50%, and 25% for high-speed cars, moderate-speed cyclists, low-speed pedestrians, and nighttime no-movement conditions, respectively. When objects move in both directions, the microcontroller senses it and increases the brightness of LEDs on both sides, sending control signals via XBee to the receiver-side microcontrollers, thereby increasing the brightness of LEDs on both sides.

4. Functioning of Designed Lighting System

The developed system is powered by a 230V, 50Hz AC supply, with a power adapter converting the voltage for use by the Arduino microcontrollers. Similarly, power is supplied to the XBee wireless communication module from the Arduino Uno microcontroller. The input sensors, including the LDR sensor, DHT11 sensor, and RCWL0516 sensor, are connected as required. Each sensor is provided with a 3.3V power supply, with their GND pins connected to the GND pin of the Arduino, and their output pins are connected to specific analog pins of the Arduino as per coding requirements. The system utilizes XBee modules for communication between streetlights. XBee S2C modules are directly connected to the Arduino Uno using the appropriate connections. These XBee modules support UART protocol and operate at the 2.4GHz frequency band, allowing communication with the Arduino using UART protocol.

Figure 2 shows the functional diagram of the designed lighting system. In this scheme, the Arduino Uno establishes communication with the connected sensors to obtain data readings from the DHT11 sensor, LDR sensor, and RCWL0516 sensors. Initially, the Arduino Uno reads the LDR sensor to determine whether daylight is present. If daylight is detected, instructions are sent to switch off the LED lights. If daylight is not detected, the Arduino collects data from the DHT11 sensor to assess weather conditions. The DHT11 sensor measures temperature and humidity. If the measured temperature is below a predefined threshold and humidity is above another predefined threshold, instructions are sent to activate the RCWL0516 sensors for object detection.

Initially, the Arduino Uno microcontroller reads the LDR sensor to determine the presence of daylight. If daylight is detected, it sends instructions to switch off the LED lights. If daylight is not detected, the Arduino collects data from the DHT11 sensor to assess weather conditions.

The DHT11 sensor measures the temperature and humidity of the local environment. If the measured temperature is below the temperature threshold value and humidity is above the humidity threshold value, instructions are sent to switch on the LED lights at a Correlated Color Temperature (CCT) of 3000K and with full brightness. This setting improves visibility in foggy weather conditions.

In this scheme, CCT represents the Correlated Color Temperature, which determines the color appearance of the LED light produced by a black body at the specified surface temperature. The temperature denoted by CCT refers to the black body's temperature, not the LED light. If the microcontroller senses that both the temperature and humidity threshold values are not satisfied, it sends instructions to switch on the LED light at a CCT of 6500K.

For this scheme, the temperature threshold value is considered as 20 degrees celsius, and the humidity is considered as 70%. These threshold values can be adjusted as needed, as it is observed that both threshold values are indicative of fog formation. For verification of fog data system, verify it with connected 3rd party weather API.

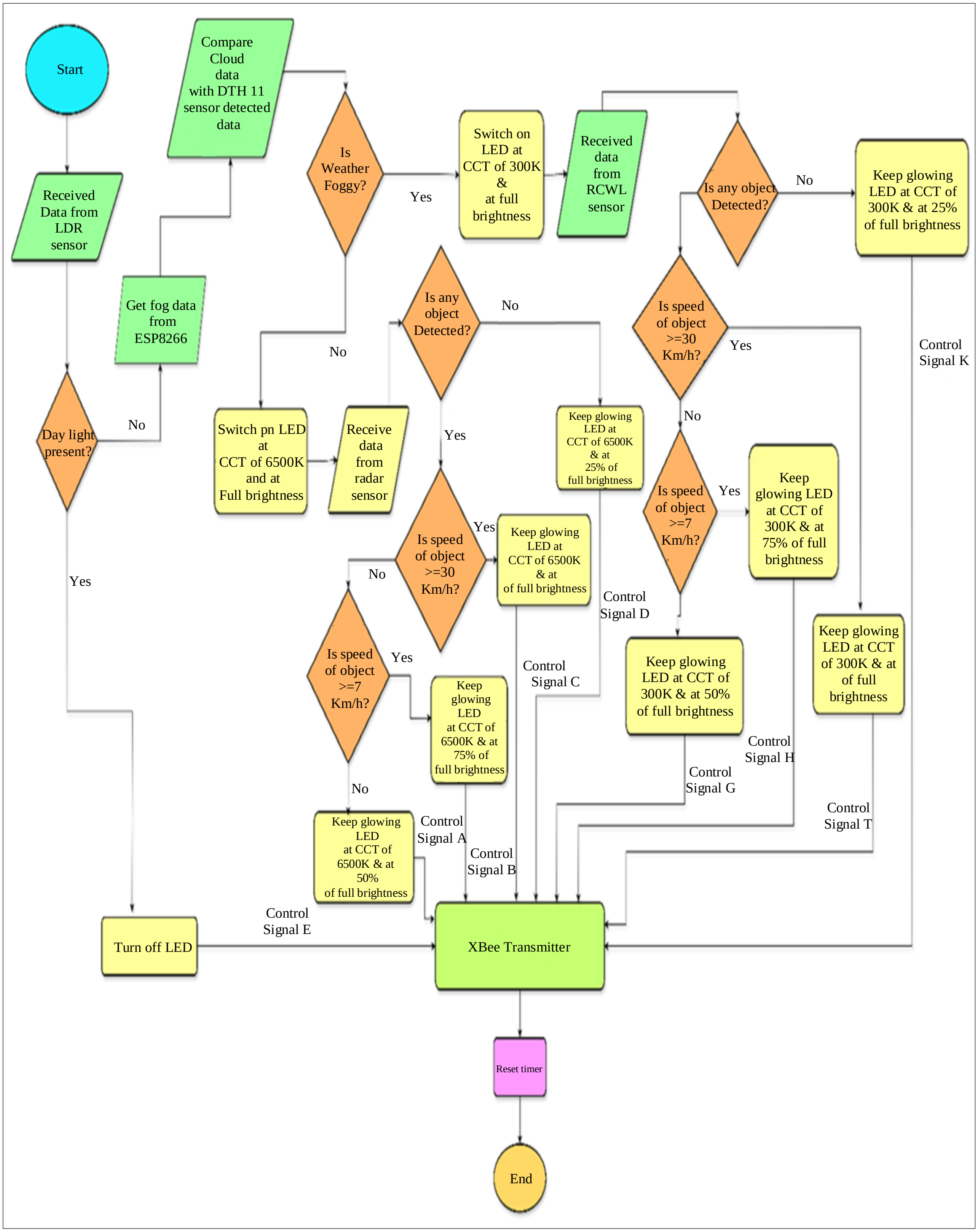

Fig. 3 Flowchart of XBee coordinator side microcontroller operation

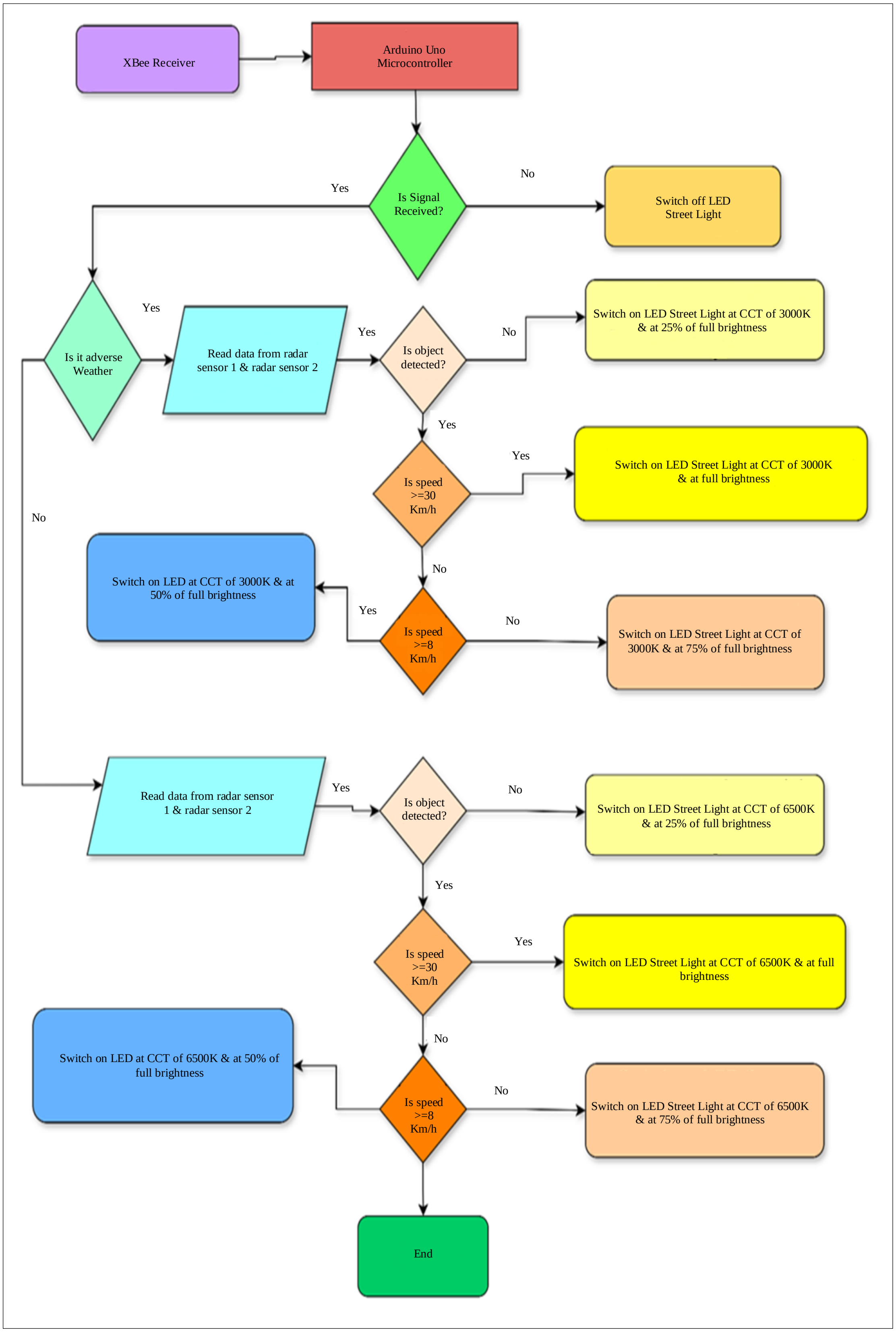

Fig. 4 Flowchart of XBee end device side microcontroller operation

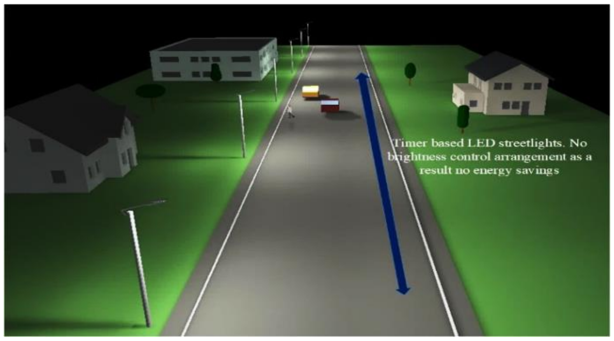

Fig. 5 Timer-based street lighting system

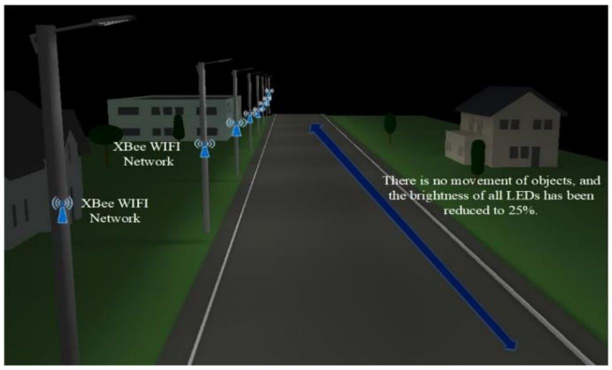

Fig. 6 XBee-based smart street lighting simulation during no object movement (25% brightness)

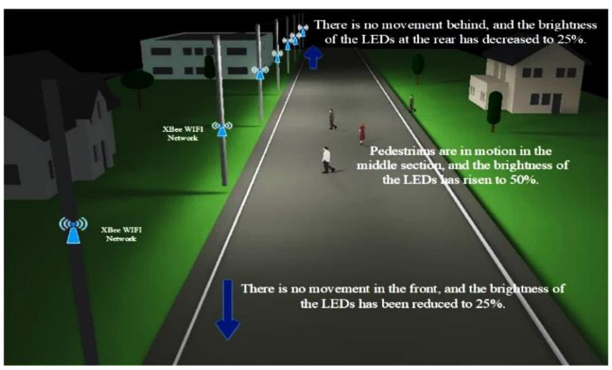

Fig. 7 XBee-based smart street lighting simulation during pedestrian movement (50% brightness)

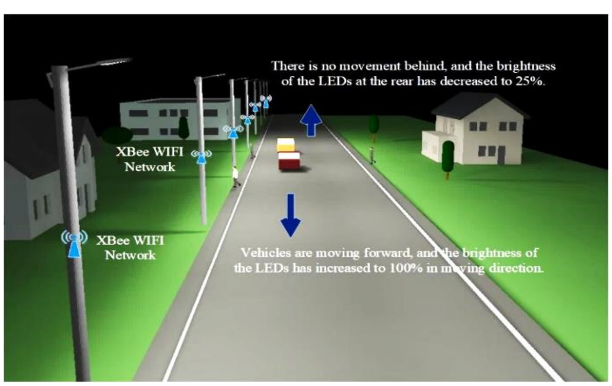

Fig. 8 XBee-based smart street lighting simulation during car movement (100% brightness)

In foggy conditions, a CCT of 3000K LED light can enhance visibility over the street surface, resulting in faster traffic movement and reduced accident proneness.

Following this protocol, the main microcontroller reads values from RCWL0516 sensor 1 and RCWL0516 sensor 2 to detect object presence. If RCWL0516 sensor 1 detects an object (value = 1), the main microcontroller instructs the LED streetlight directly connected and via XBee to increase brightness in the direction of RCWL0516 sensor 2. Conversely, if RCWL0516 sensor 2 detects an object (value = 1), the main microcontroller instructs to increase the brightness of LEDs in the direction of RCWL0516 sensor 1. If both RCWL0516 sensors detect objects (both values = 1), instructions are sent to improve the brightness of LEDs in both directions of the road.

In the prototype model, LED1 is directly connected to the main microcontroller, while LED3 is connected to another microcontroller in the direction of RCWL0516 sensor 1. Similarly, LED2 is directly connected to the main microcontroller, and LED4 is connected to another microcontroller in the direction of RCWL0516 sensor 2.

The system is controlled by an 8-bit ATmega328P microcontroller operating at 16 MHz and functioning within a temperature range from -40°C to 85°C. The microcontroller can withstand an input voltage range from 7V to 12V and produce 5V and 3.3V with its built-in voltage regulator.

The flowchart depicted in Figure 3 illustrates the workflow of the main microcontroller, continuously monitoring input sensor values. If daylight is detected, instructions are sent to switch off LED streetlights. If daylight is not detected, the microcontroller proceeds to read data from the DHT11 sensor for weather conditions.

In the case of foggy weather, LEDs are ignited at a CCT of 3000K and full brightness. For normal weather conditions, LEDs are ignited at a CCT of 6500K. Different control signals, such as C, D, G, H, etc., are generated and transmitted via the XBee transmitter to communicate with other streetlights. The XBee module serves as the coordinator, linked to the main microcontroller, enabling communication between the streetlights.

In this control scheme, a delay time of 20 ms is chosen for proper AI-based control of the main controller. Two RCWL0516 radar sensors are placed back-to-back and mounted over the main pole, facing towards the street surface. The delay time and RCWL0516 radar sensor detection instances help increase the brightness of LED streetlights in the direction of object movement.

This function is a unique control feature of LED streetlights, operating according to users' visual requirements.

This intelligent control technique aids in saving electrical power consumption, termed traffic-responsive control. This feature allows the system to adapt to the dynamic behavior of traffic conditions.

Conversely, when the LED light CCT changes, it is termed weather-responsive, as the microcontroller adjusts in response to variations in environmental temperature and humidity. Figure 4 illustrates the functioning of the receiving-side microcontroller. The receiver-side microcontroller receives data packets sent by the transmitter-side microcontroller via XBee wireless communication. XBee-based communication ensures

Security, as accessing an XBee network requires a security process. When the receiving-side XBee operates on the same channel and PAN ID, data packets are received by the XBee end device-linked microcontroller.

It then checks whether control signals C, D, G, or H are received. Based on the type of data signals received, the microcontroller adjusts or maintains the functioning of LED streetlights accordingly.

In this control scheme, when an object moves from the direction of RCWL0516 radar sensor 1 to RCWL0516 radar sensor 2, the brightness of the LED increases in the direction of the movement.

Similarly, if the system were implemented in a real streetlighting system when an object moves from the direction of RCWL0516 radar sensor 1 to RCWL0516 radar sensor 2, the brightness of LEDs in the direction of RCWL0516 radar sensor 2 would increase.

The speed of the moving object is detected by the microcontroller, depending on the delay time, which helps to adjust the brightness level of LEDs. If the detected object's speed is below 8 km/h, the system identifies the object as a pedestrian.

If the speed is between 8 km/h to 30 km/h, the system identifies the moving object as a cyclist, and if the speed is above 30 km/h, the system identifies the moving object as a motor vehicle. All types of brightness control are shown in Figures 5 to 8.

5. Developed Hardware Model

Depending on the control logic setup of the designed system of both the XBee coordinator side main microcontroller and XBee end device side microcontroller hardware setup are developed.

The experimental setup is verified for the proper functioning of the developed model. Both the figures are shown in Figures 9 and 10.

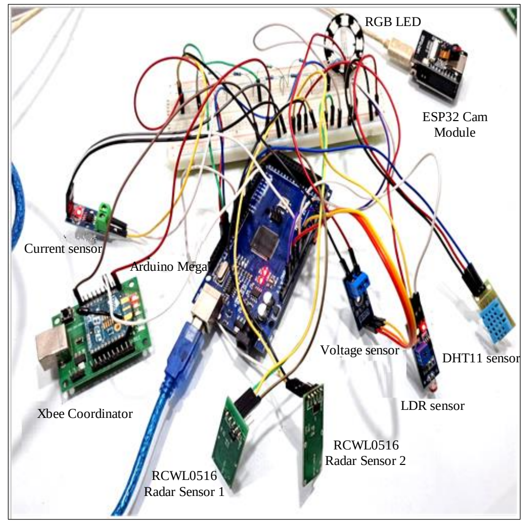

Fig. 9 Hardware prototype model of XBee coordinator side main microcontroller

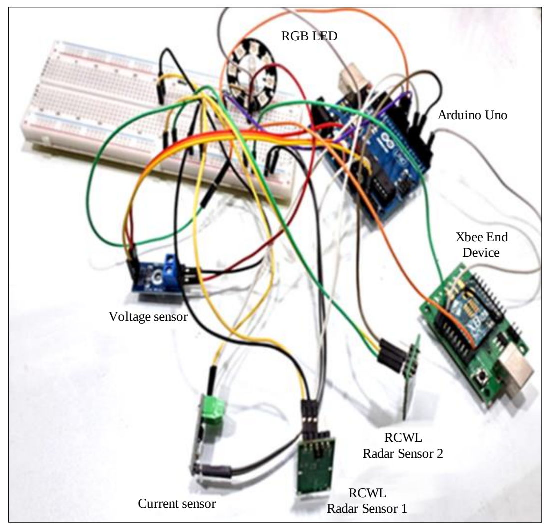

Fig. 10 Hardware prototype model of XBee end device side microcontroller

6. Detection of Moving Object and Speed

In this designed scheme, the detection of moving objects is accomplished with the help of two RCWL-0516 radar sensors. These sensors are placed back-to-back, aligned towards the street surface, to detect moving objects such as pedestrians, cyclists, and vehicles. Whenever an object enters the detection zone of either of the two radars, the system instantly records the detection timestamp [3].

When the object moves from one direction to the other, the second sensor detects it and the microcontroller also records its timestamp. By placing the radar sensors in specific directions with a certain distance between them, the system can utilize the detection timestamp delay and the detected distance gap to determine the speed of the moving object easily. This way, the microcontroller can easily calculate the speed of the object.

On the other hand, if an object enters the detection zone of one radar sensor and remains stationary, the second radar sensor will not detect it, and no second timestamp will be recorded. Using this scheme, the microcontroller will determine that the object is at a standstill. Similarly, if an object moves in both directions of the radar sensors without a detection time delay, the microcontroller will determine that objects are moving in both directions.

This approach ensures accurate detection and speed calculation of moving objects and differentiation between stationary and moving objects.

For example, Object X is moving and is detected at position A by radar sensor 1, and the same object is detected at position B by radar sensor 2. The distance between these detected positions is AB, and the time delay of detection by the two sensors is Δt. The speed of the detected object will be determined by Equation (1):

$$V= \frac{AB}{\Delta t} \qquad (1)$$

Were, V is the speed of the moving object.

Suppose object Y is detected at position A but not detected by the second radar sensor. In that case, the speed value will be a certain value (typically zero, indicating the object is stationary). If object Y and object Z are moving in both directions of the radar sensors, then the value of Δt will be zero, resulting in the speed value being infinite. In this way, the microcontroller will recognize different patterns of objects present on the street and determine the speed of the objects based on these values.

This developed system can differentiate the speed of moving objects. Whenever it detects that the speed is beyond a threshold value, it will send an instruction to the ESP32 cam module to capture a picture of the moving object.

The snapshot will be stored on a web server. Using the recorded data, traffic police can send alerts to the vehicle owner, instructing them to control their speed while driving. Failure to comply with these instructions may result in punishment. This type of control scheme can help regulate traffic speed and reduce accidents caused by high vehicle speeds, whether in normal or adverse weather conditions.

7. Fault Detection

In this system, each street lighting pole is equipped with a current sensor and a voltage sensor. During operation, the microcontroller records the current consumed by each LED and the voltage across each LED. If the current consumed by an LED is within the rated current, the light is considered healthy; otherwise, it is determined to be faulty [1, 12]. Since identical types of lamps and control gear are connected to each street lighting pole, the current, voltage, and power consumed by each streetlight should be the same.

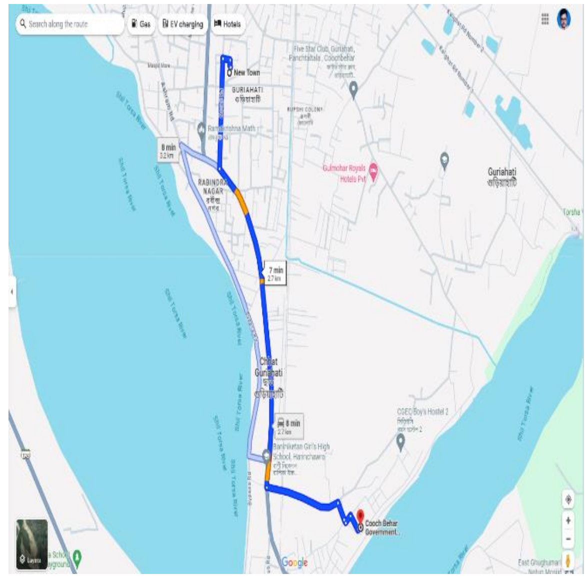

Fig. 11 A GPS tracking system snapshot

During operation, any differences in current, voltage, or power consumption patterns are recorded on a web server. This data can then be analyzed to identify discrepancies in electrical parameters. Each street lighting pole is also equipped with a GPS tracking [1] system, allowing maintenance staff to easily locate and repair faulty streetlights based on the recorded data. This ensures proper visibility on the street surface and facilitates efficient maintenance. A GPS tracking system picture is shown in Figure 11.

8. Performance Analysis of the Developed Prototype Model

In this study, the performance of the designed system is analyzed through various experimental setups to determine if the light dims correctly and to evaluate energy savings under different operating conditions of the LED light. The main purpose of these tests is to ensure that the control logic adjusts the light dimming based on object speed, ensure all sensors function properly, and verify that the control logic operates as intended. The following data setups are collected:

i) Data from all sensors connected with the main microcontroller were measured and recorded over a certain period at different operating conditions.

ii) Object detection data of RCWL0516 sensor 1 and RCWL0516 sensor 2 are collected.

(ii) The current, power consumed by the LED, and the voltage across the LED connected with the main microcontroller. Recorded data of the LDR sensor are shown in Figure 12. The recorded data of the DHT11 sensor for both temperature and humidity are shown in Figures 13 and 14.

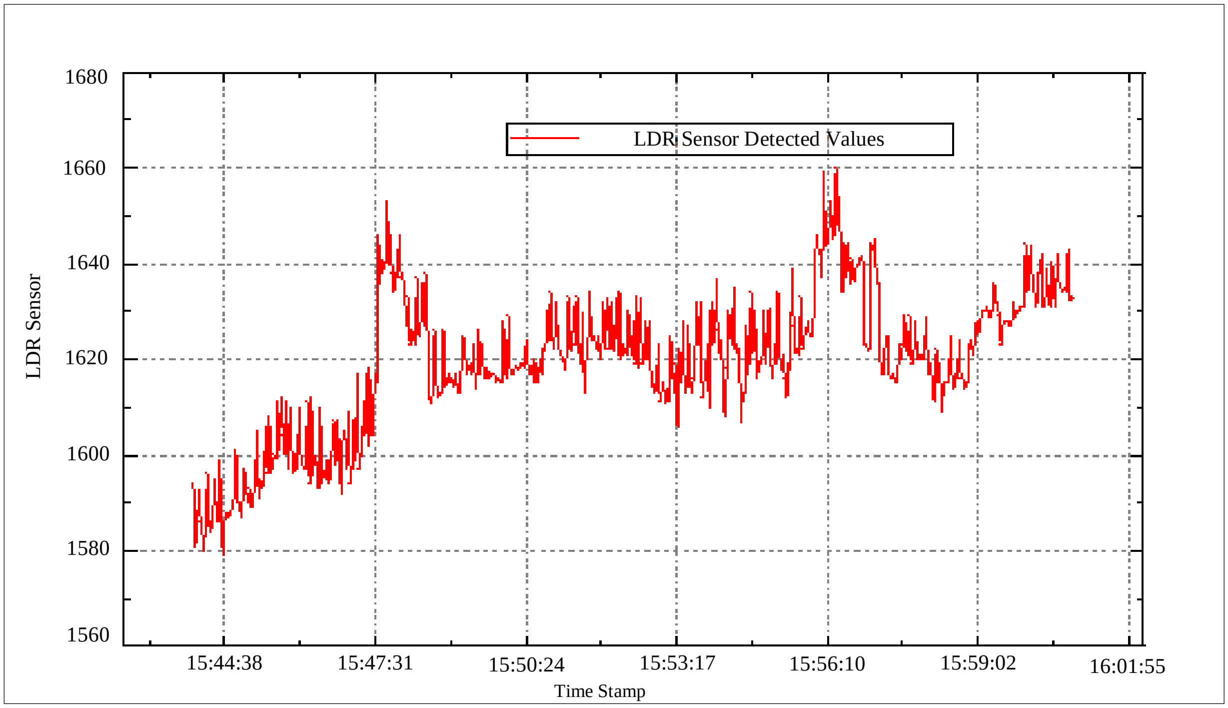

Fig. 12 Graphical analysis of LDR sensor data

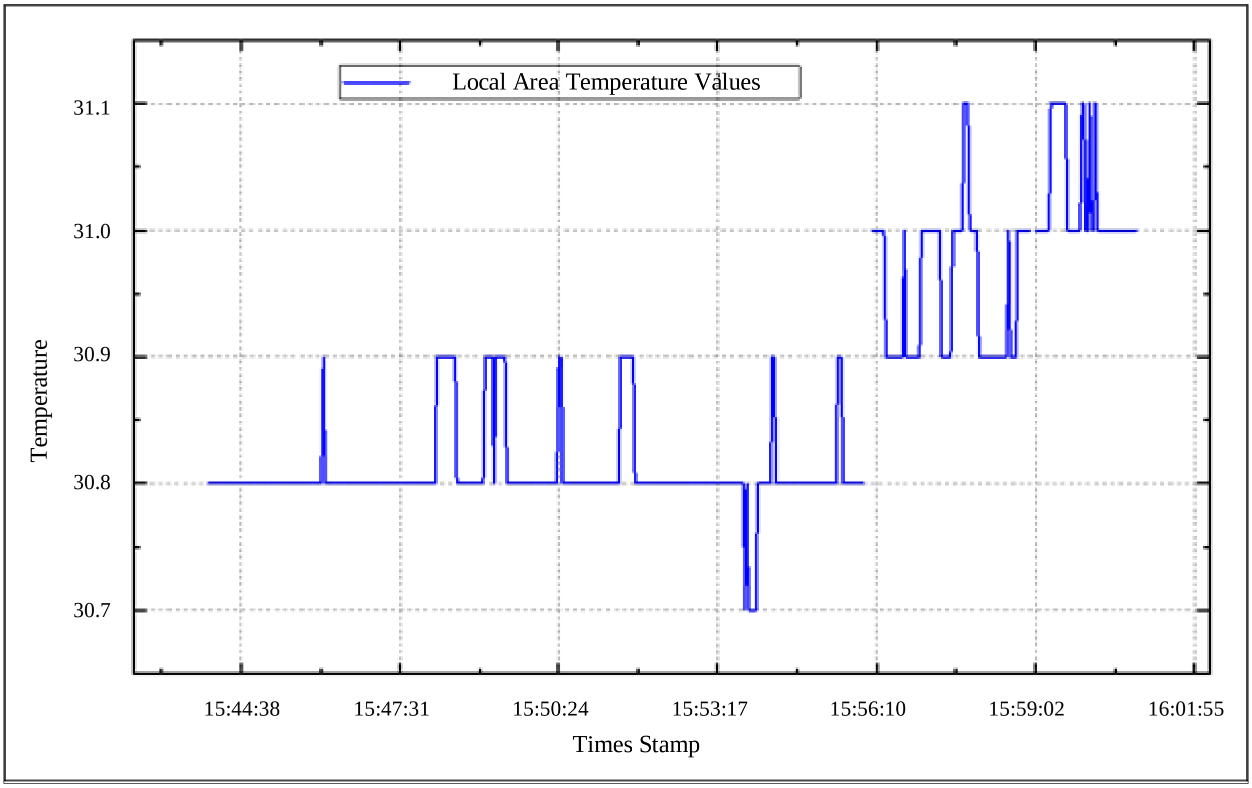

Fig. 13 Graphical analysis of temperature measured by DHT11 sensor data

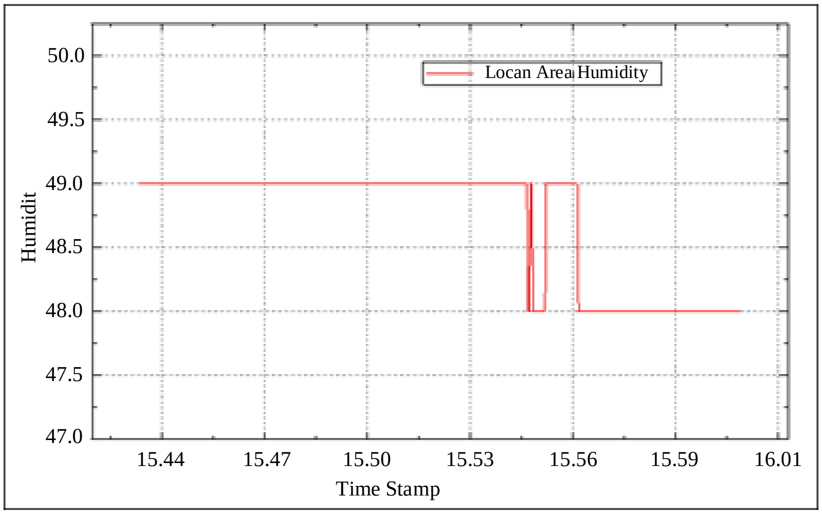

Fig. 14 Graphical analysis of humidity measured by DHT11 sensor data

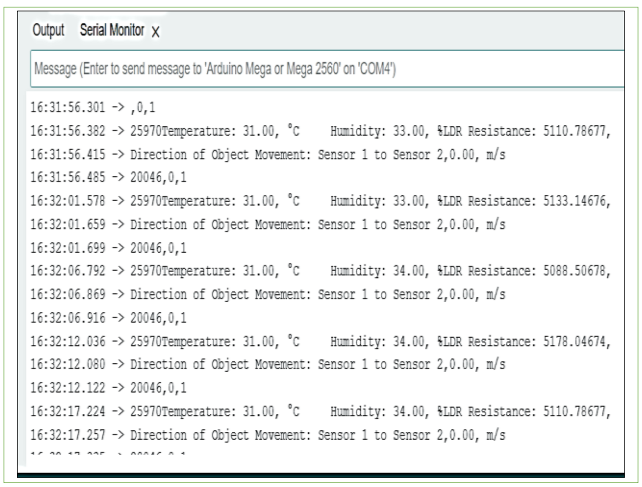

Fig. 15 Object movement from sensor 1 to sensor 2 direction with its speed

Fig. 17 Object Movement in Both Directions with Its Speed

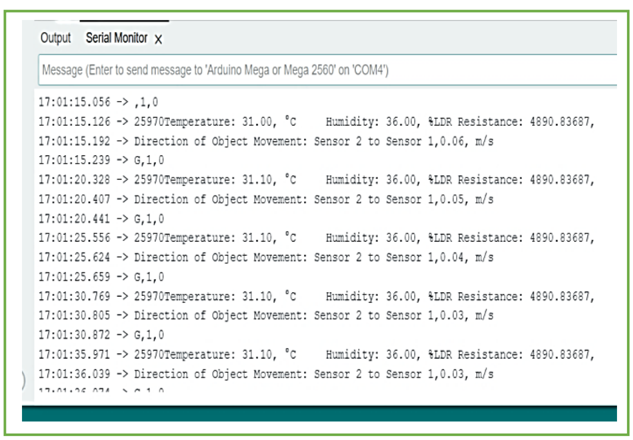

Fig. 16 Object movement from sensor 2 to sensor 1 direction with its speed

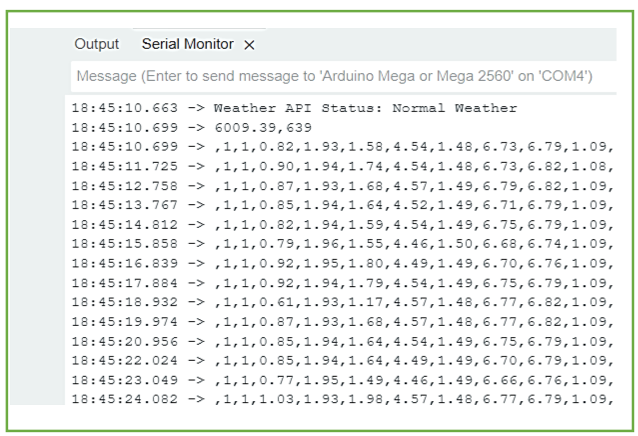

Fig. 18 Weather API forecasting message received at the main microcontroller

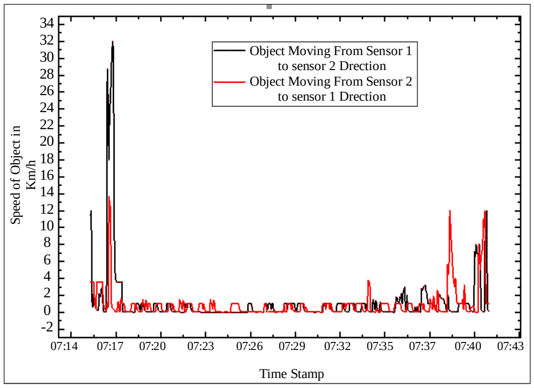

Fig. 19 Graphical analysis of object detection data and speed of moving object measurement data

From the graphical analysis shown in Figures 12 to 14, it is evident that all sensors connected to the main controller are functioning properly, and the microcontroller is functioning as per control logic and measuring the parameters accurately. This indicates that the developed system is responding properly and can be implemented for real street lighting applications.

Over the street surface, three types of speed-based objects movements: pedestrians, cyclists, and motor-driven vehicles. Depending on the practical speed of the object, they are classified accordingly. The developed prototype models have been tested by moving different speed-based objects and varying their directions of movement. In every situation, all types of object movements have been perfectly detected by the microcontroller, which also measures the objects' speeds. Figures 15 to 18 show some of the detected results. These results indicate the proper functionality of the developed system. All object movement data are recorded and plotted in Figure 19.

Table 2. Experimentally measured data during current and voltage measurement in each status of the LED

Sr. No.	LED Brightness Value	LED Illuminating at a CCT of 6500K		LED Illuminating at a CCT of 3000K	
		Current Consumed by Red Channel RGB LED (mA)	Voltage Across the Red Channel of RGB LED (V)	Current Consumed by Red Channel RGB LED (mA)	Voltage Across the Red Channel of RGB LED (V)
1.	25% Dimming	4.36	2.61	4.42	2.625
2.	50% Dimming	7.4	2.57	7.37	2.59
3.	75% Dimming	9.73	2.51	9.84	2.536
4.	Full Brightness	14.92	2.43	14.86	2.47
5.	Switch Off	0.05	0.11	0.03	0.09

For the experimental analysis, a small-wattage RGB LED has been used in this work. During the experiment, current and voltage data were recorded at different brightness and color settings, as shown in Table 2.

For graphical analysis, 500 data sets for each color and brightness setting were collected. Including this large amount of data in the paper is a very difficult task.

The developed system operates under four types of brightness conditions and two different CCT settings. Due to the vast amount of recorded data, it is challenging to incorporate all the data into this paper.

For each color and brightness condition, the current consumed by the LED was recorded over a certain period, and the recorded data are analyzed from Figures 20 to 27.

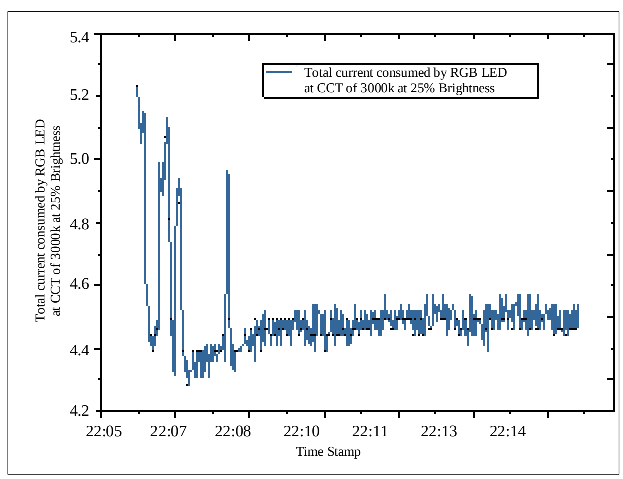

Fig. 20 Current consumed by RGB LED at CCT of 3000K and 25% brightness

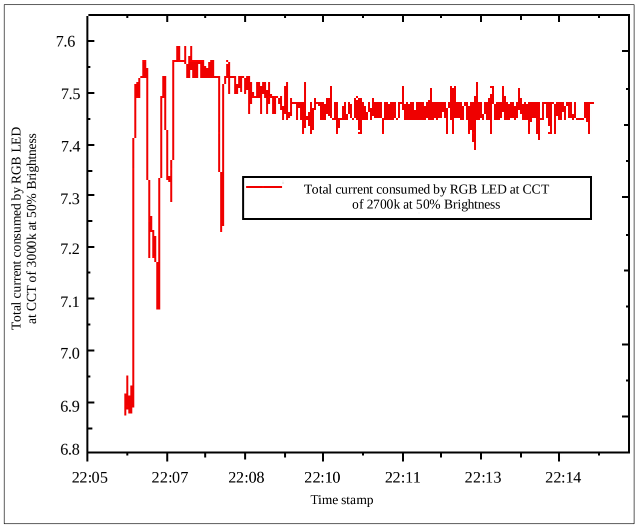

Fig. 21 Current consumed by RGB LED at CCT of 3000K & at 50% brightness

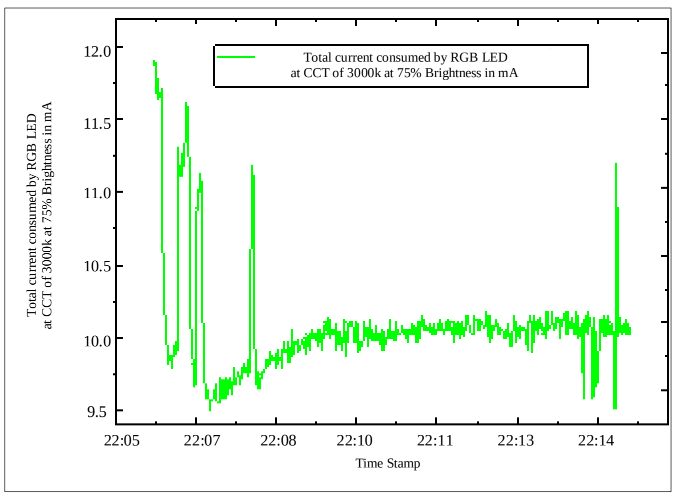

Fig. 22 Current consumed by RGB LED at CCT of 3000K and 75% brightness

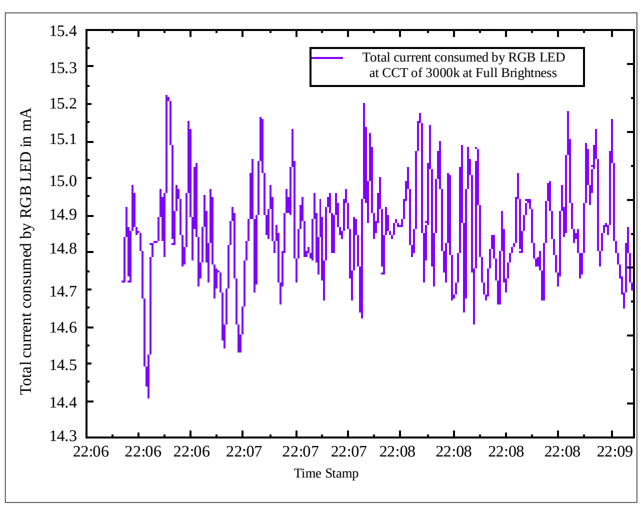

Fig. 23 Current consumed by RGB LED at CCT of 3000K and 25% brightness

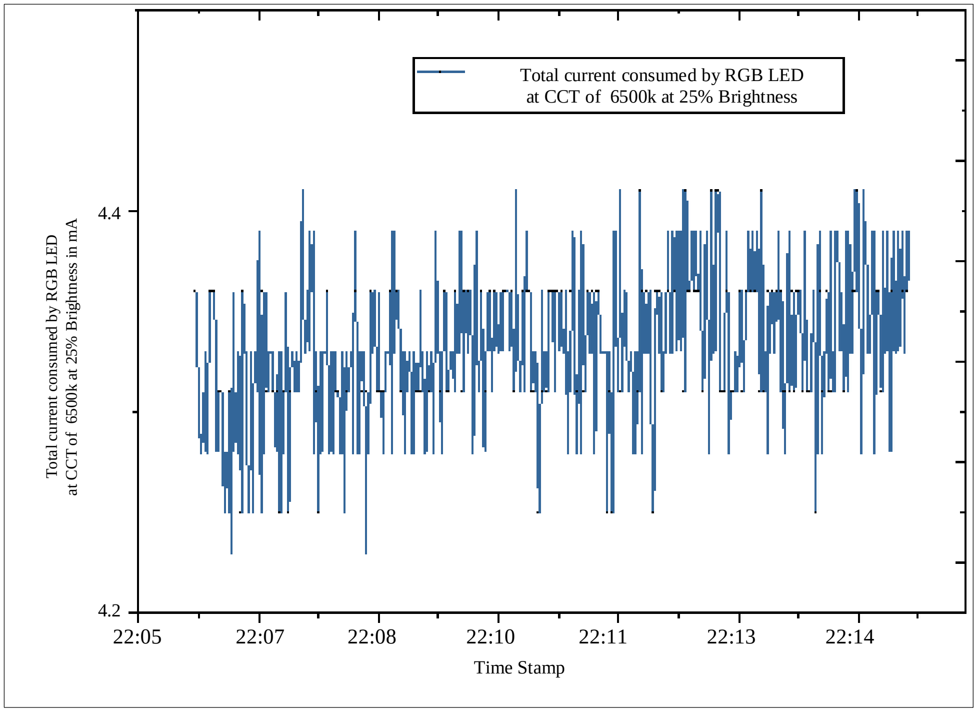

Fig. 24 Current consumed by RGB LED at CCT of 6500K and 25% brightness

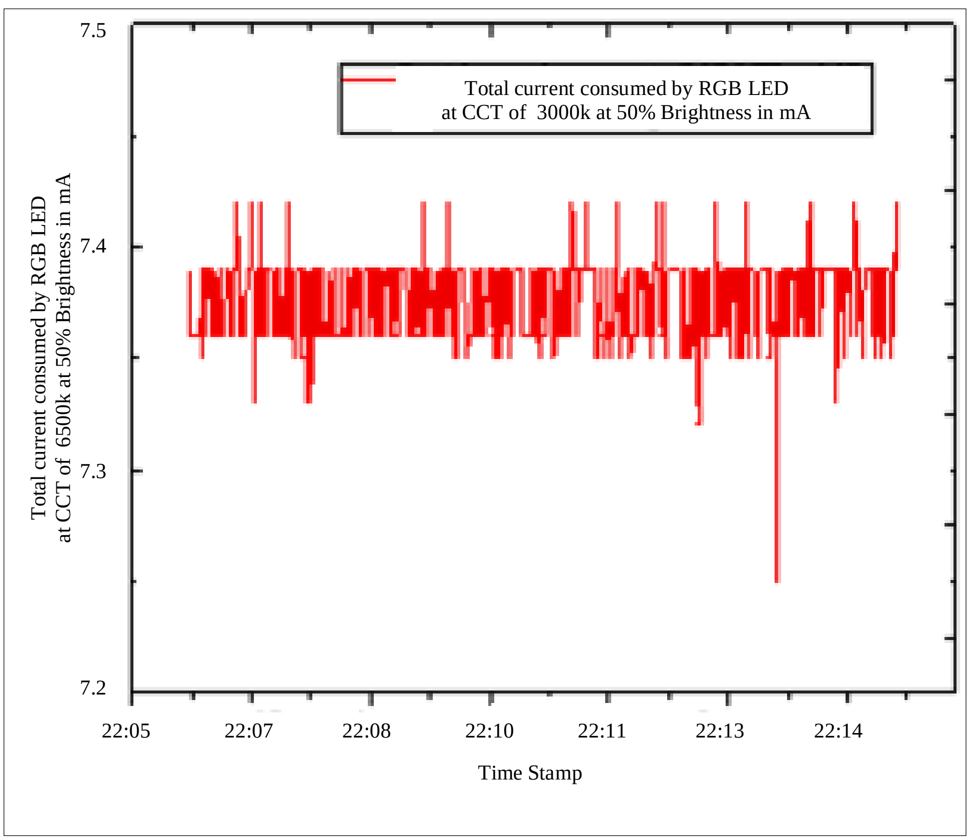

Fig. 25 Current consumed by RGB LED at CCT of 6500K and 50% brightness

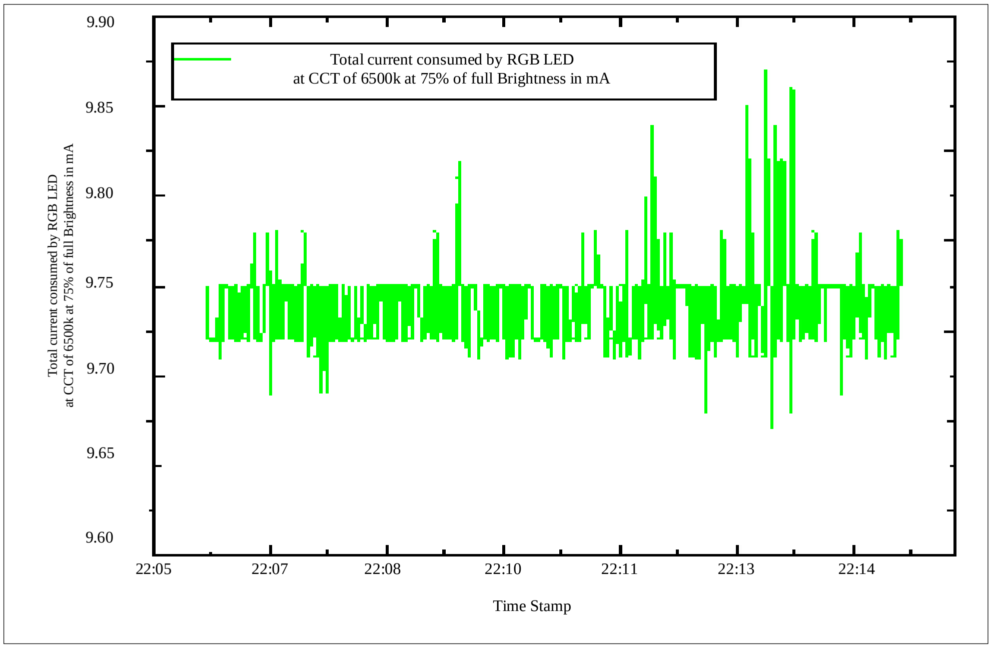

Fig. 26 Current consumed by RGB LED at CCT of 6500K and 75% brightness

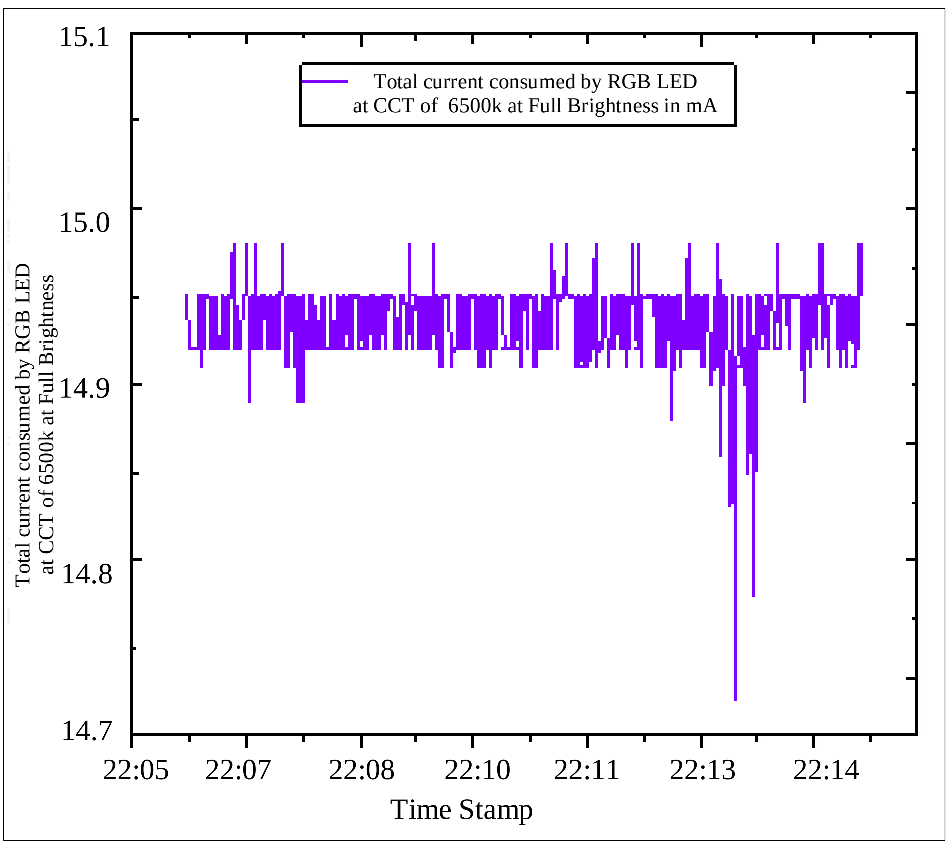

Fig. 27 Current consumed by RGB LED at CCT of 6500K and full brightness

During the experiment, the power consumed by the LED under each condition was also recorded. The power consumption for the two different color settings and four types of brightness setups are shown in Table 3.

Normal timer-based street lighting systems consume the same amount of power throughout the night, independent of whether traffic is present on the street surface or not. On the other hand, the designed lighting system adjusts brightness depending on the presence as well as the speed of the object. Power consumed by the RGB LED for each condition of color and brightness adjustment is calculated. A comparison of the percentage of power consumed by the normal lighting system and the designed lighting system is performed and plotted in Figure 28.

Table 3. Experimentally measured data during current and voltage measurement in each status of the LED

Sr. No.	Brightness Values	Type of Traffic Movement	Power Consumption at CCT of 6500K (Normal Weather Conditions) in mW	Power Consumption at CCT of 3000K (Foggy Weather Conditions) in mW
1.	25%	Vacant Street	11.37	11.58
2.	50%	Pedestrian	19.01	19.08
3.	75%	Cyclist	24.42	24.89
4.	100%	Motor-Driven Vehicle	36.25	36.70

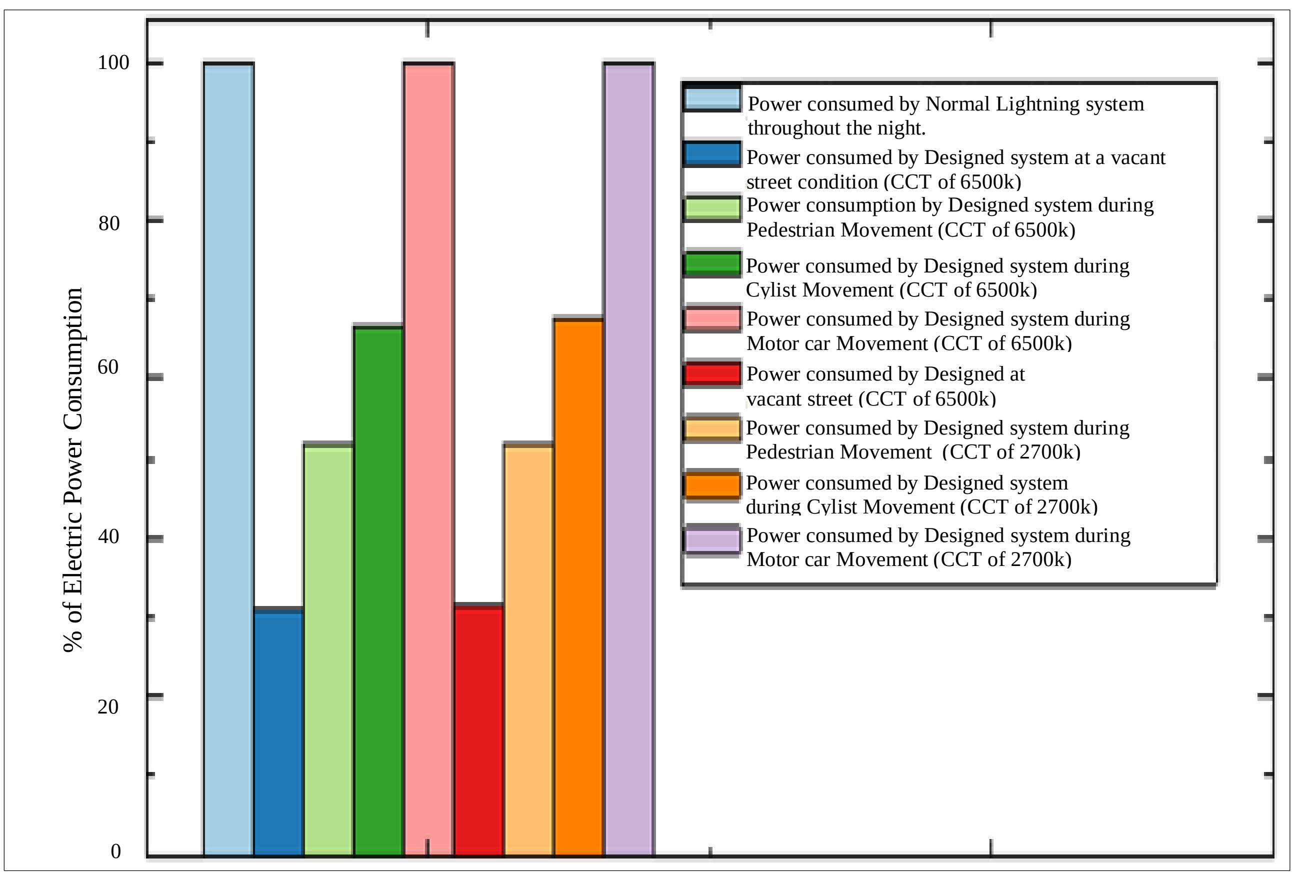

Fig. 28 Graphical analysis of the percentage of power consumed by normal lighting system and designed lighting system at both warm white and cool white conditions

9. Result Analysis of the Designed System

In this system, an Arduino Mega acts as the main microcontroller and receives data from various input devices: an ESP32-CAM module, an LDR sensor, a DHT11 sensor, a current sensor, a voltage sensor, and two RCWL-0516 radar sensors. Depending on the control scheme uploaded in the code, it responds to traffic movements and weather conditions.

To test the proper functioning of LED streetlights in response to environmental temperature and humidity, data from weather API was used for verification. This weather API data helps to identify the type of weather at the present situation at that street surface and to tune RGB LED to provide suitable visual effects for the street surface users. During the experiment, the prototype model responded as per the control logic at each testing step, indicating proper weather-responsive behavior.

Traffic responsiveness characteristics were also tested by placing and moving objects at different positions and varying speeds within the detection zone. Pictorial views of different lighting control arrangements are shown in Figures 6, 7 and 8. This dynamic brightness control setup helps to save energy without compromising the required light level on the street surface.

10. Conclusion

This research introduces a smart street lighting solution that responds to traffic speed and foggy weather conditions by adjusting the brightness and color temperature of RGB LEDs from cool white to warm white, thereby enhancing visibility in adverse foggy conditions. In each object detection case, the ower consumed by the LEDs is also monitored, which helps to reduce electrical energy consumption.

Additionally, if any light is defective, the system provides guidelines to detect and identify faulty LED lights, aiding in the maintenance of the lighting system.

This designed solution not only improves visibility and saves energy but also ensures the reliability and efficiency of street lighting by promptly identifying and addressing any issues with the LED.

A functional hardware prototype model is developed to verify the proper functioning of the designed system. During experimental analysis, the microcontroller, sensors, and LED lights operated accurately, dimming the LEDs during low-speed object movement and increasing brightness during high-speed object movement to save energy. This dynamic brightness and color control is an intelligent solution integrated into a single system.

It helps control traffic speed by alerting high-speed vehicle owners and improves visibility without increasing electrical energy consumption. Compared to existing lighting systems, this designed system uniquely combines weather-adaptive and traffic-adaptive features.

Additionally, the system reduces installation and maintenance costs by utilizing a single lighting fixture instead of two. Overall, this smart street lighting solution offers variations in a light color and brightness control, reducing overall energy usage without increasing electrical energy consumption.

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