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Next-Gen Smart Street Illumination System: An Adaptive and Energy-Efficient Approach to Street Lighting

Preksha Chaturvedi
Department of Computer Applications,
Babu Banarasi Das University,
Lucknow, India
perkschat@bbdu.ac.in

Riya Pandey
Department of Computer Applications,
Babu Banarasi Das University,
Lucknow, India
riyapandey2608@bbdu.ac.in

Nidhi Saxena
Department of Computer Applications,
Babu Banarasi Das University,
Lucknow, India
nidhi.shivansh@bbdu.ac.in

***Abstract*- The increasing urbanization of cities has increased demand for affordable, environmentally friendly, and efficient street lighting solutions. Conventional street lighting systems often lead to unnecessary energy waste since they operate at maximum intensity regardless of real usage patterns. The " Next-Gen Smart Illumination System" uses motion sensors, energy-efficient LED lights, and intelligent control algorithms to get around these problems.**

This system uses motion detecting technology to dynamically change the streetlights' lighting intensity.
IoT connectivity integration allows for remote management and real-time monitoring, which facilitates fault detection, usage analytics, and maintenance optimization.
Energy efficiency and intelligent automation are combined in this system to minimize carbon footprints, improve public safety, and guarantee ideal lighting conditions. It is in line with the worldwide objectives of energy conservation and smart city development, and it is a step forward in sustainable urban infrastructure.

***Keywords**: Energy- efficient lighting, Motion detection, public safety, Smart control Algorithm, IoT connectivity, Dynamic lighting, Energy conservation.*

1. INTRODUCTION

For public areas to be safe, secure, and accessible, street lighting is an essential part of the infrastructure. However, regardless of actual usage, old street lighting systems frequently run at full intensity all night long, wasting a lot of energy and raising expenses. The need for smarter, more sustainable, and energy-efficient solutions has grown critical as urbanization picks up speed.
To tackle these issues, the " Next-Gen Smart Illumination System" presents a revolutionary solution. Utilizing energy-efficient LED lights, motion sensing technologies, and sophisticated control algorithms, this system maximizes streetlight utilization. When not in use, lights use less energy by running at a lower intensity. When motion is detected, lights automatically brighten to provide sufficient illumination where and when it is needed.

The system also has Internet of Things (IoT) connectivity, which makes real-time monitoring possible. In addition to lowering operating expenses, this integration improves the dependability and effectiveness of maintenance procedures. The objectives of smart city development and sustainable urban infrastructure are in line with this smart lighting system's emphasis on lowering energy use, carbon footprints, and enhancing public safety. It offers a progressive response to the rising energy needs of contemporary cities.

Fig. 1.1: Adaptive street light control system [2]

2. LITERATURE REVIEW

Recent advancements in street lighting systems emphasize adaptive and intelligent controls to enhance energy efficiency and sustainability.

Shavkatov (2023) introduced a smart lighting system utilizing IoT for adaptive illumination, reducing energy usage and light pollution [1].

Zulfizar (2023) explored motion-sensing and automated dimming to optimize real-time lighting adjustments, achieving operational cost savings [2].

Balázs et al. (2023) highlighted the energy-saving potential of traffic-regulated lighting systems, demonstrating significant reductions in power consumption without compromising safety [3].

Gapit et al. (2023) developed a simulation environment for dimming control systems, showcasing adaptable methods to optimize LED streetlight performance through advanced control strategies. This simulation-based approach enables testing and fine-tuning of control algorithms in diverse scenarios, offering a scalable solution for intelligent lighting systems [5].

Collectively, these studies emphasize the importance of integrating adaptive technologies, such as IoT, fuzzy logic, and traffic regulation, to achieve energy efficiency and sustainability in urban lighting. However, gaps remain in integrating diverse control systems, conducting long-term cost analyses, and ensuring compatibility with existing infrastructure. Future research should address these issues by focusing on scalable, unified frameworks that optimize functionality while reducing costs.

3. PURPOSE AND SCOPE

3.1. Energy Efficiency
Streetlights that are intelligently activated and dimmed depending on contextual information and motion sensing use less energy. Late at night, for example, low base lighting is kept on unless motion is detected.

3.2. Accurate Motion Classification
Accurate motion type identification (e.g., human, vehicle, animal) is ensured by integrating motion features (speed, intensity, duration, and trajectory) with an ML model. This lessens unnecessary triggers and increases response.

3.3. Enhanced Public Safety
Street safety and visibility are improved, particularly at night, via instant activation and brightness modification upon identifying people or cars.

3.4. Reduced False Positives and Negatives
Reliable system performance is ensured by reducing inaccurate detections by cross-validation, noise removal, and feedback loops.

3.5. Adaptability to Context
Optimal visibility in a variety of situations is ensured by adjusting lighting levels according to environmental factors (such as fog, time of day, and traffic).

3.6. Continuous Improvement
Over time, system intelligence is increased by improving motion classification, sensor thresholds, and weights through the logging of detection data and retraining of the machine learning model.

3.7. Cost Savings
For towns or organizations implementing the system, lower operating costs are achieved through energy-saving techniques and less maintenance requirements.

3.8 Environmental Benefits
The technology supports sustainability initiatives by minimizing unnecessary lighting and optimizing energy use.

4. METHODOLOGY

4.1 Pre-requisites

4.1.1 Sensors

- **PIR –**
  PIR sensors perceive heat from the infrared radiation that is naturally released by things like people and animals. Motion inside its detecting zone causes the sensor to detect variations in the amount of infrared radiation.

- **Ultrasonic-**
  Ultrasonic sensors are devices that identify objects by using high-frequency sound waves. They can detect items in a variety of conditions, such as those with dampness, filth, or extremely high or low temperatures because they don't require physical contact to function.

- **Radar-**
  They sense movement, measure distances, and detect things.

- **Ambient Light Sensors-**
  They transform the energy of light into an electrical signal, which is then processed to calculate the amount of illumination.
  More precise measurements for applications that focus on people are ensured by sophisticated models that replicate the sensitivity of the human eye to light.

4.2.2 Pre-Trained Machine Learning Model:

This algorithm requires machine learning model that have previously been trained to identify patterns or carry out tasks like picture classification on a dataset, which is usually big and varied.

4.2 Algorithm

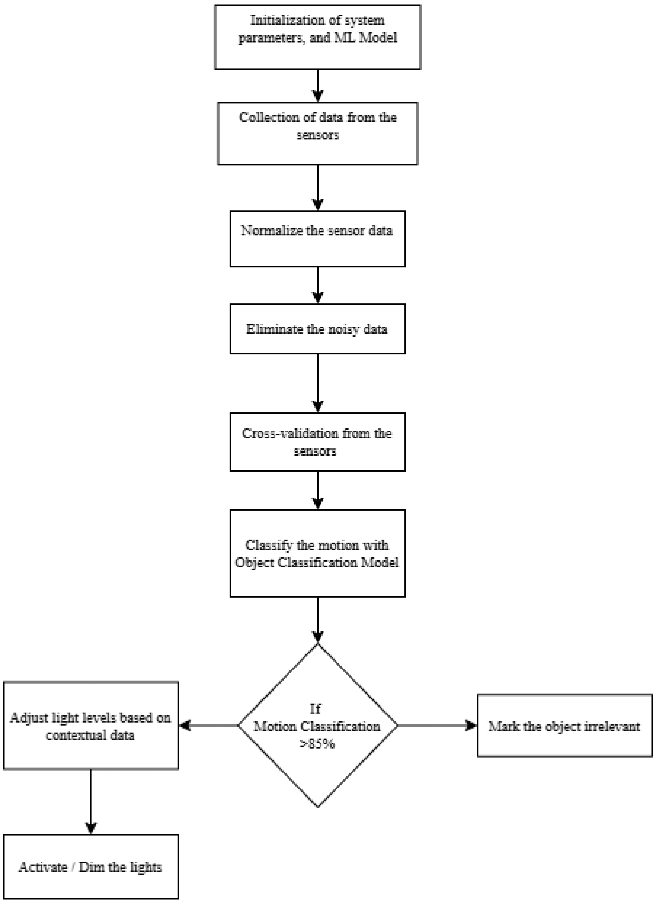

Fig. 4.1: A simple flowchart depicting the work-flow of the algorithm used.

Step 1: Initialization

(i) System Parameters
- Threshold Motion level (t_{motion})
- Lighting Intensity
- Sensor weights for fusion

(ii) Load ML Model on a dataset of motion patterns

Step 2: Sensor data

(i) Collect data from sensors
(ii) Normalize to common Range [0, 1] for easy analysis.

Step 3: Sensor data processing

(i) Eliminate noisy data
(ii) Cross-validate motion detected by sensor.
(iii) Combine weighted output of sensors:

$$S_{fused} = W_{pir}.S_{pir} + W_{ultrasonic}.S_{ultrasonic} + W_{radar}.S_{radar}$$

Where, S_{fused}, S_{pir}, $S_{ultrasonic}$, S_{radar} stands for sensor fusion output, and outputs from PIR, ultrasonic, and radar sensors respectively; and, W_{pir}, $W_{ultrasonic}$, W_{radar} stands for PIR, ultrasonic, and radar sensor weights respectively.

Step 4: Motion Classification

(i) Extract Speed, intensity, duration, and trajectory from the sensor.
(ii) Provide these features as input in the ML Model. Classify the Motion as human, vehicle, animal, or irrelevant.
(iii) If the model output Confidence > 85%, proceed to the next step else, it is irrelevant.

Step 5: Context Decision

(i) Retrieve contextual data
Eg: Increase responsiveness with increase in traffic, increase sensitivity of system with increase in fog, etc.
(ii) Modify lighting levels based on motion type, time of day, and weather conditions.

Eg: If a pedestrian is detected, medium brightness is activated; any vehicle detected, high intensity brightness activated; or, at late night low-base brightness is activated until a motion is detected.

Step 6: Lighting Control

(i) Activate lights if motion detected from human or vehicle.
(ii) Apply Energy-savings strategies by deactivating or dimming lights in no-motion.

Step 7: Feedback and Learning

(i) Log Detection data stores instances of false positives, and false negatives for future analysis.
(ii) Use data from log to train ML Model for further improvement.

5. RESULT ANALYSIS

This section presents a detailed analysis, comparing the conventional lighting systems and our proposed system on the basis of three major parameters-

- **Energy consumption** – The amount of energy consumed by the bulb,
- **Operating cost** – The cost of electricity for lighting the bulb, and
- **Carbon emissions** – The amount of carbon dioxide released into the atmosphere by illumination of bulbs.

For analysis, we considered a tiny dataset. Two street lamps, of 150W each, were put under observation for 1 hour. One lamp was based on the conventional street lighting system, and the other one was based on the smart street lighting system that we are proposing.

It was observed that the traditional lamp was illuminated for the whole 1 hour, while the smart lamp was illuminated for 50 minutes. The average intensity of each of the bulb was found to be 100% and 75%, respectively.
To calculate the energy used by each lamp, we used the formula:

Energy = Power x Time

Here, the power used by the traditional lamp is 150W, that equals to 0.15 kW, and the running time is 1 hour, thus, the energy used by the traditional, E_1 is:

$$E_1 = 0.15 \text{ kW x } 1 \text{ hour} = 0.15 \text{ kWh}$$

While, the power used by the smart lamp at an average 75% intensity is:

$$\text{Power} = 150\text{W x } 0.75 = 112.5\text{W} = 0.1125 \text{ kW}$$

And, the running time of the smart lamp is:

$$\text{Time} = \frac{50}{60} \text{ hours} = 0.8333 \text{ hours}$$

Thus, the energy used by the smart lamp, E_2 is:

$$E_2 = 0.1125 \text{ kW x } 0.8333 \text{ hour} = 0.09375 \text{ kWh.}$$

The electricity cost of a street bulb, in India, costs between ₹6 - ₹10 per kWh. The average electricity rate considered for analysis is ₹8 per kWh. The cost of illumination can be calculated as:

Cost = Energy consumed x Electricity rate

The cost of running the traditional street light, C_1 is:

$$C_1 = 0.15 \text{ kWh x ₹8/ kWh} = \text{₹}1.20.$$

The cost of running the smart street light, C_2 is:

$$C_2 = 0.09375 \text{ kWh x ₹8/ kWh} = \text{₹}0.75.$$

The carbon emissions are calculated using the carbon intensity of electricity, which is approximately 0.9 kg CO_2/kWh. The carbon emissions are calculated as:

Carbon emission = Energy consumed x carbon intensity

The amount of carbon emission the traditional street light generating, CE_1 is:

$$CE_1 = 0.15 \text{ kWh x } 0.9 \text{ kg } CO_2\text{/kWh} = 0.135 \text{ kg } CO_2.$$

The amount of carbon emission the smart street light generating, CE_2 is:

$$CE_2 = 0.09375 \text{ kWh x } 0.9 \text{ kg } CO_2\text{/kWh} = 0.0844 \text{ kg } CO_2.$$

Table 5.1: Comparative data analysis of the three factors in traditional street lights vs the smart street lights

	Traditional Street Lights	**Smart Street Lights**
Energy Consumed	0.15 kWh	0.09375 kWh
Operational Cost	₹1.20	₹0.75
Carbon Emission	0.135 kg CO_2	0.0844 kg CO_2

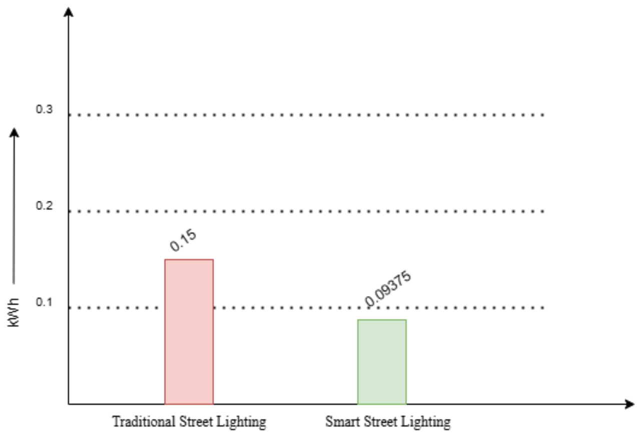

Fig. 5.1: Comparison of Energy consumption of traditional street light vs smart street lighting systems

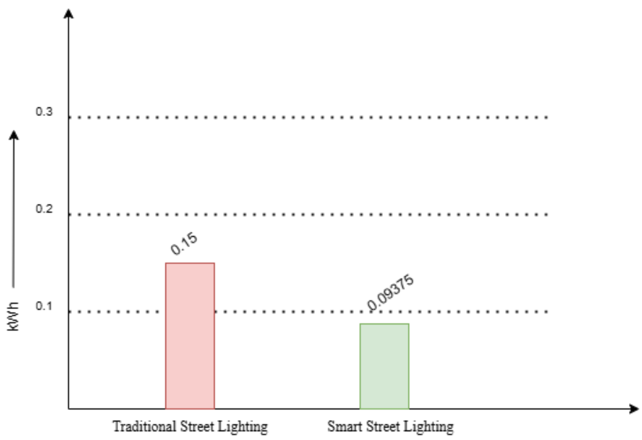

Fig. 5.2: Comparison of operation cost of traditional street light vs smart street lighting systems

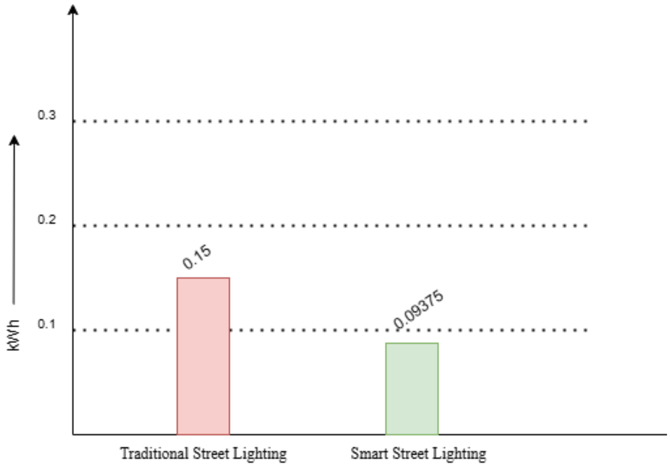

Fig. 5.3: Comparison of carbon emission of traditional street light vs smart street lighting systems

Thus, we can see a significant reduction was found in energy consumption, operational cost and carbon footprint when the smart street lighting system was used. These findings highlight the potential of smart lighting systems to enhance sustainability while minimizing costs and environmental damage.

6. FUTURE SCOPE

The future scope of this research moves to solve problems such as the reduction of installation expenditures by making better integration of sensors, smart lightbulbs, networking systems and installation facilities. New developments can ease the system's design, lower the capital costs, and facilitate the deployment for wider use. Also, in the context of increasing exposure to privacy risks, the system may enhance the risk of exposure concerns by applying privacy-enhancing technologies which limit data collection, especially where IoT sensors or cameras are used. Likewise, combining smart streetlights powered by solar, with energy storage systems will lead to self-sustainable systems while improving energy efficiency and reducing the reliance on the traditional electrical grids. All the above improvements aim an ultimate goal of bringing about smart streetlighting systems with lower deployment costs, less intrusive of user's privacy and cleaner in the environment.

7. CONCLUSION

In conclusion, the smart street lighting systems propounded would change the face of urban infrastructure by integrating energy-efficient, sustainable, and green technologies. Apart from environmental sustainability, this would lower both operating costs as well as public carbon emissions and energy consumption. Apart from the conservational effects, it assures safety to the municipality by offering protection against crime and sickening street lighting. The adaptability and scalability would find this work suitable for cases ranging from isolated rural areas to elaborately populated urban ones. Therefore, smart street lighting shows the variants of establishing an even smarter, safer, and sustainable orientation towards cleansing the immediate problems faced with respect to energy efficiency and environmental protection in the present world.

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