Streetlight Inventory and Illuminance Mapping with Low-Cost IoT and Cloud-based GIS Integration for Enhanced Energy Efficiency

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Abstract— **In contemporary cities, ensuring consistent and effective illumination is imperative for the sustained functionality of urban landscapes. The public lighting infrastructure is essential to maintaining people's safety and well-being. However, the inventory of this infrastructure are costly. The study's goal is to present a GIS-based mobile sensing approach as a low-cost car-mounted IoT device that helps to collect and analyze information on traditional street lamps used for public lighting, with a focus on how it might be used without the use of complicated or expensive technologies. The seamless integration of GPS and Geographic Information System (GIS) technology, which increases the system's overall capabilities, is the system's key technological achievement. The solution uses a cloud-based GIS environment to provide data display through a Web GIS dashboard with an intuitive interface, empowering decision-makers. This dashboard simplifies data analysis, promotes efficient decision-making, and lays the groundwork for important developments in urban lighting infrastructure. Additionally, this technology goes beyond data gathering by acting for increased energy efficiency. It introduces an inventive approach positioned to expedite the early stages of a city's digital evolution toward smart city status, particularly beneficial for cities facing budget constraints. It provides policymakers and administrators with the means to optimize energy consumption patterns, lower expenses, and eventually generate fiscal savings for governmental bodies and taxpayers by identifying regions with energy surpluses. Beyond their financial advantages, this innovation has far-reaching effects on the public's overall quality of life and have established a pattern for future improvements in urban lighting systems.**

Keywords: Public lighting, Energy efficiency, IoT, GIS, Cloud, Smart City.

1. Introduction

Cities are under growing pressure to become more sustainable, efficient, and resilient as the world's population continues to grow [1,2,3,4]. Implementing innovative strategies and technology that support sustainable development, such as improving streetlight efficiency, is one way that cities can accomplish these aims [5,6,7]. Cities may hasten the achievement of the Sustainable Development Goals (SDGs) by utilizing the potential of the Internet of Things (IoT) [8,9], embedded systems [10,11], and other smart technologies [12,13,14]. Access to reliable and efficient lighting is essential for the functioning of cities and communities [15,16]. Public lighting infrastructure plays a key role in ensuring the safety and well-being of citizens and visitors during nighttime hours [17, 18]. However, managing and maintaining the traditional infrastructure can be a complex and costly task [19]. The system presented in this study serves as a transformative catalyst for cities at the dawn of their digital evolution. Its cost-effective and practical approach tailored for budget-strapped municipalities not only accelerates the path towards smart city status but also symbolizes an opportunity for inclusive and sustainable urban development.

To address this challenge, we have developed a system for collecting, analyzing and map data on traditional public lighting infrastructure. Our system utilizes an on-board sensor platform that can be mounted on vehicles, allowing for collection, and recording illuminance data during nighttime driving. By addressing several signal processing problems that are fundamental to mapping public lighting levels, identifying streetlights illuminance on the GIS, comparing their locations to the recorded light values, and identifying those that are not working, our system aims to make the management and maintenance of public lighting infrastructure more efficient and cost-effective.

Our system architecture is structured into four layers for system design, each important for reliable service. The first layer, sensors, collects data like streetlight and GPS coordinates. The second layer, data logging, stores and organizes this data for easy access. The third layer processes the raw data using spatial ETL techniques for distribution through web services. The fourth layer offers customizable applications for users to analyze the processed data efficiently.

2. Literature

The application of GIS-based systems in street lighting management leads to optimized operation and maintenance of streetlights, resulting in reduced energy consumption and cost savings [20]. The use of advanced technologies and the effectiveness of street lighting are topics covered in recent research articles and publications [21,22,23]. For example, Amjad Omar et al. article "Smart City: Recent Advances in Intelligent Street Lighting Systems [24] focuses on the most recent developments in IoT-powered intelligent street lighting systems. This study highlights the benefits of IoT-based street lighting systems, such as improved energy efficiency and reduced maintenance costs.

The paper "Green IoT for Eco-Friendly and Sustainable Smart Cities: Future Directions and Opportunities" [25] by Faris Almalki et al. is also notable since it provides a comprehensive review of techniques and strategies aimed at making cities smarter, sustainable, and eco-friendly through the integration of Internet of Things (IoT) technology. It highlights the importance of addressing pollution hazards, traffic waste, energy consumption, and cost management to create environmentally-friendly smart city applications, while also discussing future research challenges and opportunities in this field.

Kabir Kazi Amrin et al. present "Energy Efficient Street Lighting: A GIS Approach" [26], which outlines a GIS-based approach for efficiently collecting data on street lighting. This approach encompasses measurements of lighting levels, uniformity, energy consumption, and energy classifications. The methodology entails capturing nighttime images of illuminated streets, computing average illuminance and electrical power consumption for each street segment, and then manually integrating this information into desktop GIS software to assess power consumption distribution and cost-effective illumination coverage of pavement areas.

In "Intelligent Energy Efficient Street Light Controlling System based on IoT for Smart City" [27] by M. C. V. S. Mary et al., the authors propose an intelligent street lighting system that leverages sensors and automation to significantly reduce energy consumption. This approach offers a more sustainable and cost-effective alternative to traditional manually-operated systems.

These studies collectively emphasize the potential advantages of employing smart technologies to enhance the energy efficiency of street lighting systems. By harnessing location-based data and smart controls, it becomes feasible to minimize energy usage, lower operational expenses, and elevate the overall performance of street lighting infrastructure.

The common limitation in some existing approaches is that they often employ light sensors disconnected from real-time GIS integration. Moreover, the mapping process relies heavily on interpolation techniques, generating raster GIS layers based on interpolated light values. The unique aspect of our IoT system is its integration with a cloud GIS, enabling an automated end-to-end process. From data collection, real-time data transfer, data extraction, transformation, and loading, to geoprocessing and analysis on the cloud, the whole workflow is seamlessly connected and automated. Additionally, this technology extends beyond data gathering; it acts as a catalyst for heightened energy efficiency. It empowers policymakers and administrators to optimize energy consumption patterns, reduce expenses, and ultimately generate fiscal savings for governmental bodies and taxpayers by identifying regions with energy surpluses.

3. Methodology

A. Architecture

The system layered architecture (Fig. 1) is intended to be highly structured, with tasks being clearly divided across four distinct layers. Each layer is essential to the complete functioning of the system and must perform flawlessly to provide end-users with a dependable and effective service.

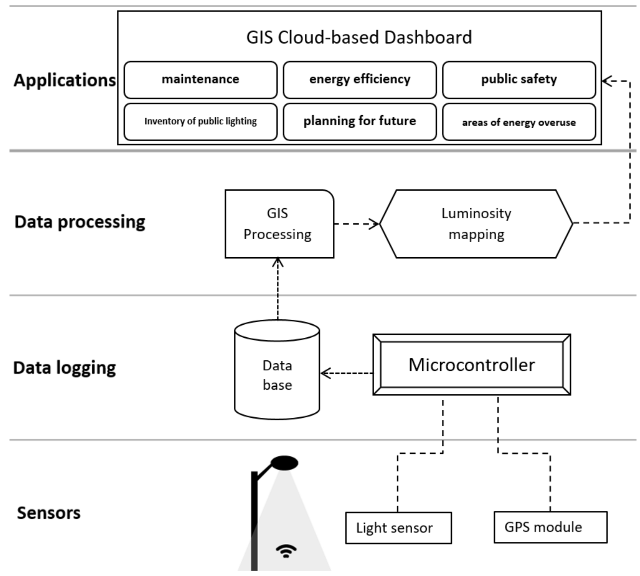


Fig. 1. System architecture

The organization is envisaged for the system design, with tasks being clearly separated into four different tiers. Each layer is essential to the system's overall operation and must operate faultlessly to give end users a dependable and efficient service.

Data collection is the responsibility of the sensors layer, which is the first layer of the system. The sensors collect data from streetlights and GPS coordinates for each value of sensed light value thanks to their fixed installation to the car's roof. The light sensor is able to gauge light levels in lux.

The second layer is the data logging system. This layer records all the sensor data gathered by the sensors layer. It stores the data in a format that can be easily accessed and analyzed by the subsequent layers of the system. The data logging system is designed to be reliable and efficient, ensuring that all data is recorded accurately and securely.

The third layer is responsible for processing the raw data collected by the sensors and stored in the data logging layer. This layer integrates the data, using a three-phase process where we use a spatial ETL to extract, transform and load the data. The processed data is then distributed through map-based web services for remote access and simple map display.

The fourth and final layer is dedicated to potential applications. This layer is designed to provide users with access to the processed data and tools to utilize it for various purposes. The applications layer is highly flexible and can be customized to meet the specific needs of different users. It is designed to be user-friendly, providing easy access to information and tools required to analyze the data.

B. *Car-mounted system*

The circuit design System (Fig. 2) describes the electronic components of the system. The Adafruit TSL2591 is used to measure the light in lux using an Arduino Mega 2560 R3. we employed the Ublox NEO-6M GPS Module to record GPS coordinates during each light measurement. This module not only provides precise location information but also keeps track of the current date and time. We use a SIM800L, a small quad-band GSM/GPRS module with a quad-band antenna, to ensure real-time monitoring. It is used to connect to the internet and communicate date, location, and light value information to the cloud. A portable and user-friendly 16x2 LCD screen is also used. The collected data can be also stored in a flash memory connected through the convenient USB port, ready to be analyzed and processed in any GIS platform. The components of the car-mounted system are listed in Table 1.

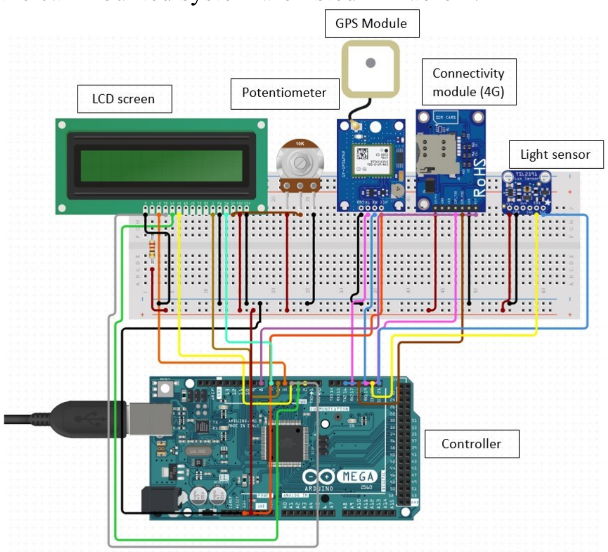
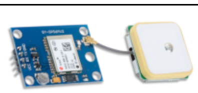
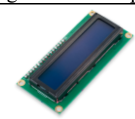


FIG. 2. CIRCUIT DESIGN OF THE CAR-MOUNTED SYSTEM

The light sensor was calibrated through making sure it was clean and that the apparatus was ready, zero-calibrating the lux meter by covering the sensor, span-calibrating it with a known light source, and confirming its accuracy by comparing readings to a reference lux meter under a variety of lighting conditions.

TABLE 1. USED HARDWARE COMPONENTS IN THE CAR-MOUNTED SYSTEM

Hardware	Description
 Light sensor	An ultra-high-range luminosity sensor with an I2C interface, the TSL2591 is more accurate than low-cost LDR photocells and can detect light ranging from 188 uLux to 88,000 Lux. A semi-spherical shape was employed to detect illumination from various angles.
 GPS module	The NEO-6M-0-001 is a GPS module use to determine its location. This device connects to GPS satellites. Lat & Long, time, and date are transmitted as the returned value via serial communication..
 Connectivity module	SIM800L is a compact quad-band GSM/GPRS module with a quad-band antenna. It is used to access the internet and send light values coordinates and date to the cloud.
 Single-board computer	Arduino Mega 2560 R3 microcontroller board served as the control board. Our system's central processing unit, this board was in charge of collecting and analyzing data from a variety of sensors and infrastructure-related parts for public lighting.
 LCD 16x2	A small LCD screen, allowing the display light values in Lux.
 Rotary potentiometer	LCD 16x2-related resistive-type transducer that translates angular or linear displacement into an output voltage by sliding a contact along a resistive element's surface.

C. *Illuminance measurement*

In order to relate illuminance data to streetlamps, the light sensor is set up so that it precisely records values on the roof's horizontal surface while the car moves through city streets.

The schematic diagram below (Fig. 3) demonstrates the point where the extracted illuminance values in our pilot case was extracted and then related to streetlamps, as well as how the height of the vehicle and the source of light all converge at a nearly perpendicular angle from the source to the roof of the vehicle.

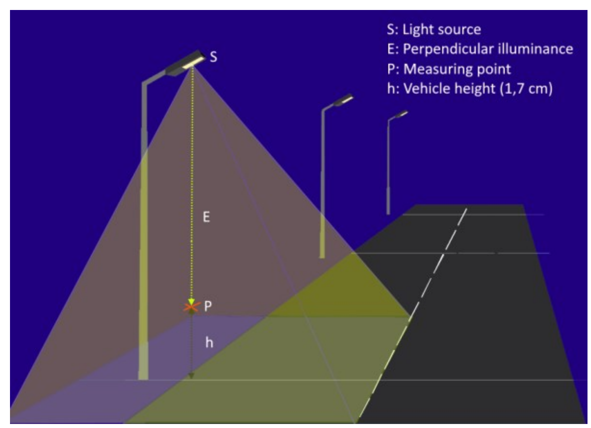


FIG. 3 SCHEMATIC DIAGRAM OF ILLUMINANCE DATA COLLECTION AND RELATIONSHIP TO STREETLAMPS

D. *GIS processing and analysis*

The process begins by importing the data into the GIS environment. To do this, we utilize an automatic data interoperability tool, organizing the data into columns that included the lux value and geographical coordinates representing the illumination data as a set of XY coordinates, each point being no more than 5 meters apart. Subsequently, a geoprocessing tool is employed to create a raster layer by interpolating a surface from these points, utilizing the inverse distance weighted (IDW) technique depending the mask of the buildings. By transforming the data into a spatial format, the GIS software becomes able to recognize and display the information on a map, allowing for a comprehensive visualization and analysis of the data based on its geographical location. This resulted in a choropleth map that visually depicted the distribution of streetlights' illuminance across the streets on a satellite image or a base map (Fig. 4).

With the data readily accessible on the map, we utilize the spatial analysis tools to conduct a thorough analysis of the distribution of street lighting. For instance, we are able to identify areas with low or high light intensity using spatial analysis tools. Also, processing performs a proximity analysis to distinguish between streetlights that were functioning properly and those that were not. Illuminance measurements are grouped into predetermined lighting classes in Geographic Information Systems (GIS) based on local authority guidelines that are customized specifically for pedestrian zones and low-speed traffic sectors. The second edition of CIE 115:2010 [28] offers guidance for illuminance classes to improve energy economy, as seen in Table 2.

TABLE 2. LIGHTING CLASSES FOR PEDESTRIAN AND LOW SPEED TRAFFIC AREAS (CIE 115:2010 2ND EDITION)

Lighting Class	Average horizontal	Minimum horizontal	Additional if facial recognition requirement is necessary	
	illuminance Eh,av in Lux	***illuminance Eh.min in Lux***	***Minimum vertical Illuminance Ev,min in Lux***	***Minimum semi-cylindrical illuminance Esc,min in Lux***
P1	15,0	3,0	5,0	3,0
P2	10,0	2,0	3,0	2,0
P3	7,5	1,5	2,5	1,5
P4	5,0	1,0	1,5	1,0
P5	3,0	0,6	1,0	0,6
P6	2,0	0,4	0,6	0,4

Considering the design and attributes of the streetlights within the pilot case area, we have categorized the status of these streetlights as outlined in the table 3.

The measurements are matched with the appropriate classes by the application. Color codes are then used to transform this data into visual representations on digital maps (fig. 6). This method makes it easier to spot places with different illumination levels and improves our knowledge of how illuminance classes are distributed.

TABLE 3. CLASSIFICATION OF STREETLIGHT STATUS BASED ON THEIR RELATED ILLUMINANCE LEVELS

Streetlights status	**Lighting Class in Lux**
Adequate Illuminance	10 to 20
Underperforming	5 to 9,9
Non-Functional	<5
Overly Bright	>20

E. GIS dashboard for improved Decision-Making

After ensuring that the feature class is in the correct format and contains the desired attributes and geometries, it is then updated in a hosted web feature service (WFS) to make it accessible over the internet regardless of location. To do this, we use a cloud web GIS platform that provides the tools and capabilities needed to share the spatial data as a WFS. One such platform is ArcGIS Online, which is widely recognized as one of the best options available, depending on our specific needs and requirements (fig. 5).

We also created a web GIS dashboard with many widgets that offers data analysis and a wealth of information and insights based on the WFS. This dashboard can be consulted directly from a web browser.

4. RESULTS AND DISCUSSIONS

The application of GIS and geoprocessing tools has demonstrated its effectiveness in mapping street lighting data. The figure 6 provides a visual representation of illuminance levels across a pilot case area. This map delineates areas with high, low, and adequate illuminance, categorizing streetlights into four distinct groups: Adequate Streetlights, Underperforming Streetlights, Non-Functional Streetlights, and Overly Bright Streetlights depending the illuminance classification in table 3.

Real-time data display is facilitated through a web GIS dashboard that showcases a time series of data at various vehicle locations (Fig. 7). The inventory of streetlights has been comprehensively mapped and analyzed, with key performance indicators (KPIs) prominently featured, as illustrated in the figure 7.

The pilot case encompasses a total of 40 streetlights, with the following breakdown: 4 non-functional, 7 underperforming, 18 overly bright, and only 11 with adequate illuminance. Notably, the overly bright streetlights collectively yield an illuminance sum of 697.1 lux, averaging 38.72 lux per streetlight. This excessive illuminance is indicative of heightened energy consumption.

This inventory includes data on 40 streetlights, each of which has a distinct Streetlight ID, lux-level illumination, geographic coordinates (POINT X and POINT Y), and the state of its operation. Based on their brightness, the streetlights are divided into four different categories. Notably, the inventory's illuminance levels range widely; they range from 1,920 lux to 125,228 lux. The data shows a range of operational conditions, with some streetlights operating as intended and others being either overly bright, underperforming, or not functioning at all. These insights are helpful for boosting energy efficiency, lowering operational expenses, and managing streetlights more effectively.

Our proposed GIS-based mobile sensing approach, utilizing low-cost car-mounted IoT devices, introduces an accessible and cost-effective solution for cities at the outset of their digital journey.

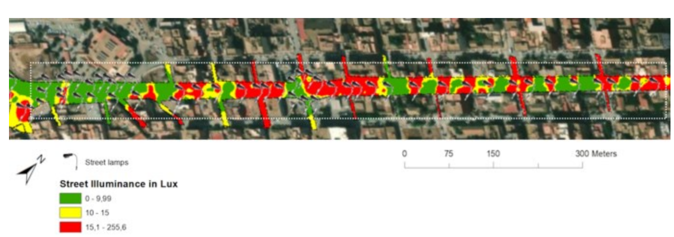


FIG. 4. STREETLIGHTS ILLUMINANCE MAP OF THE PILOT CASE

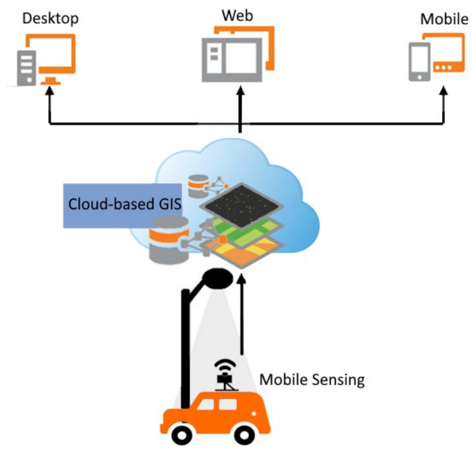


FIG. 5. WEB GIS CONCEPTUAL DIAGRAM

This approach streamlines the collection and analysis of data concerning traditional street lamps, bypassing the need for complex and expensive technologies. This accessibility is crucial for municipalities in the nascent stages of embracing digital transformations.

The amalgamation of GPS and Geographic Information System (GIS) technology within our system stands as a pivotal achievement. This integration markedly enhances the system's efficiency in gathering comprehensive information about urban lighting infrastructure. By leveraging these technologies, decision-makers gain access to a cloud-based GIS environment featuring a user-friendly Web GIS dashboard. This dashboard serves as an invaluable tool, simplifying data analysis and empowering stakeholders with a clear interface for informed decision-making. Beyond its data-driven capabilities, our system extends its impact by acting as a catalyst for improved energy efficiency. It provides a roadmap for policymakers and administrators to optimize energy consumption patterns, thereby reducing operational costs and identifying surplus energy regions. These insights can yield substantial fiscal savings for governmental bodies and taxpayers, positioning the system as a cost-effective investment with tangible financial benefits.

Moreover, the societal impact of this technology transcends financial gains. By enhancing the efficiency and reliability of public lighting, our system contributes significantly to the overall quality of life within urban environments. Well-lit streets foster a sense of security and promote a safer environment, thereby laying the groundwork for continued advancements in urban lighting systems and overall infrastructure management.

The mapping of streetlights and the integration of GIS technologies hold significant promise in enhancing energy efficiency through the improved management and control of street lighting systems. GIS enables precise illuminance mapping, facilitates data collection and analysis, and ultimately empowers the optimization of energy consumption and cost reduction [29,30].

It is evident that GIS technologies play a pivotal role in illuminance mapping, data collection, and analysis, ultimately enabling precise assessment and optimization of energy consumption in street lighting systems [31]. This approach not only facilitates effective decision-making regarding energy-efficient lighting but also offers a strategic pathway for municipalities and urban planners to better manage and control street lighting infrastructure. By harnessing the power of GIS, stakeholders can further refine strategies aimed at sustainability, cost-effectiveness, and improved urban lighting management.

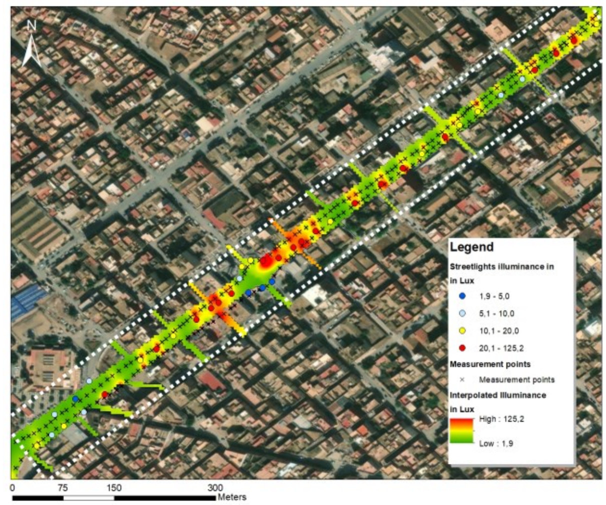


FIG. 6. STREETLIGHTS ILLUMINANCE CLASSIFICATION

FIG 7. WEB GIS DASHBOARD OF STREETLIGHTS INVENTORY

5. CONCLUSION

Our study has illuminated the potential of our presented solution as powerful allies in the realm of street lighting management. Through meticulous mapping and analysis, we've successfully categorized streetlights across a pilot case area into four distinct groups, shedding light on their operational status and illuminance levels. This data, displayed in real-time through a web GIS dashboard, empowers decision-makers with the essential insights required to optimize energy consumption and reduce operational costs. The data collected from the inventory of 40 streetlights paints a diverse picture, with illuminance levels ranging from 1,920 lux to 125,228 lux. This diversity underscores the significance of our efforts to manage street lighting more effectively, enhancing both energy efficiency and cost-effectiveness.

Our long-term goal is to make this system into a digital public lighting system for cities. This would give decision-makers a solid foundation for assessing and improving the performance of traditional public lighting, with a strong emphasis on lowering energy use. Additionally, the system's capability to continuously check the efficiency of streetlights can improve public safety by enabling rapid maintenance. The system detailed in this study presents an innovative approach poised to catalyze one of the initial phases of a city's digital transformation towards becoming a smart city.

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