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Design of an Intelligent Energy Management Prototype for an Electric Lighting Network on a Raspberry Pi Board

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Abstract. Efficient management of street lighting is crucial for cities seeking to reduce their energy consumption and greenhouse gas emissions. This paper proposes an innovative approach that dynamically adjusts the brightness of streetlights according to two key factors: traffic density and weather conditions. Traffic density is assessed in real time by an image processing system using the YOLOv8 algorithm, which identifies and counts vehicles captured by the cameras. At the same time, the level of cloud cover is measured by an LDR photosensor connected to a Raspberry Pi, which analyzes the ambient light intensity. These data are transmitted to the Raspberry Pi via the MQTT protocol, where a neural network model, trained beforehand, predicts the optimal operating cycle of the street lamps to adjust their brightness in real time. The results show that this method, combining machine vision, IoT and artificial intelligence, delivers significant energy savings without compromising user safety, offering a promising solution for modern cities.

Index Terms—Intelligent Street lighting, Energy efficiency, Neural networks, Internet of Things (IoT), YOLOv8.

1 Introduction

Street lighting represents a significant expense for municipalities, with significant energy, economic, and environmental repercussions. According to a report by the International Energy Agency, this sector is responsible for around 6% of the world's electricity consumption. This high proportion highlights the importance of street lighting in the overall energy balance, underlining the need to optimize lighting systems to reduce their environmental impact while achieving substantial savings for local authorities [1].

Traditionally, street lighting is managed according to predefined cycles, without taking into account actual traffic and ambient light conditions. This static management inevitably leads to energy wastage during periods of low traffic or clear skies, and can also result in insufficient lighting during busy periods or adverse weather conditions, compromising visibility and user safety.

In recent years, technological advances in the fields of artificial vision [2], the Internet of Things (IoT) [3], and artificial intelligence (AI) [4] have made it possible to envisage more dynamic and intelligent management of street lighting. Automatic detection of vehicles and real-time analysis of cloud cover now make it possible to continuously adjust the brightness of streetlights according to actual needs.

Our research is in line with this approach, proposing an innovative solution that combines these cutting-edge technologies. The aim is to develop an autonomous system capable of analyzing video streams and weather data to intelligently modulate urban lighting. This approach aims to achieve substantial energy savings while maintaining optimum visibility for road safety.

Theoretically, this project draws on recent advances in convolutional neural networks for object detection, and deep learning for the prediction of complex non-linear models. In practical terms, it requires the integration of various hardware and software components into a scalable, high-performance IoT (Internet of Things) architecture.

In short, this research project encompasses technological, energy, economic, environmental, and safety issues. Its success could have a concrete and measurable impact on the sustainable development of urban infrastructures and foster the transition to smarter, more resource-efficient cities. Furthermore, this

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research project follows the work carried out in articles [5], [6], and [7].

2 Related Works

Numerous studies have been carried out on intelligent lighting systems, with the aim of optimizing energy consumption and improving public lighting management.

[8] presents a street lighting system designed to improve a city's energy efficiency. The system automates the switching on and off of street lamps, activating them in the evening before sunset and switching them off in the morning when there is sufficient natural light. The system detects vehicle movements or human presence on the road, enabling only a portion of the streetlights ahead of the movement to be switched on and those behind to be switched off, thus reducing energy consumption. What's more, the system incorporates sensors to detect faulty streetlights and sends an SMS to the control authority via a GSM modem to take the necessary action.

[9] describes an intelligent street lighting system using GSM technology to improve energy efficiency and facilitate maintenance. Unlike traditional wired systems, which are often rigid and difficult to install, this wireless system monitors and controls streetlights remotely, enabling rapid fault detection. The system harnesses solar energy to power the streetlights, using solar panels to charge the batteries during the day, which then power the lamps at night. Lighting automatically adjusts according to vehicle or pedestrian movements, the real-time clock, and ambient light intensity. A microcontroller processes the information from the sensors and transmits it to a control station via a Raspberry Pi module, using SMS for communication. The system includes a graphical user interface (GUI) for visualizing the status of the streetlights, resulting in energy savings, reduced maintenance, longer life and better overall system performance.

[10] proposes an automated street lighting management system using IoT to save energy by automatically adjusting the intensity of LED lamps according to ambient light and weather conditions, measured by a temperature and humidity sensor (DHT11). The system, controlled by an Arduino board, replaces energy-hungry HID lamps with more efficient LEDs, reducing energy waste and improving performance over traditional systems.

[11] describes a smart city application where an island of lampposts is entirely controlled remotely. Each streetlight uses an electronic board for its local management, and a ZigBee network transmits data to a central unit, based on a Raspberry Pi board. For remote control, a WiMAX connection was tested and implemented, overcoming the limitations of Wi-Fi networks. The system was designed, built and tested in the field over a period of several months.

[12] proposes an automated public lighting management system to reduce energy consumption by using variable intensity LED street lamps. The system, applied to a school campus, turns on the lamps when an object is detected, and adjusts the light intensity using a Raspberry Pi module and a Pi camera. The detection of objects, including people, is achieved using computer vision techniques, which effectively reduce energy consumption.

[13] proposes an Internet of Things (IoT)-based automated street lighting control and monitoring system to solve problems associated with manual systems, such as high maintenance costs and suboptimal utilization. The system uses various sensors, a microprocessor, actuators, and a software GUI to improve streetlight management. Experimental results show that this automated system enables more satisfactory management, with reduced maintenance costs and greater precision.

3 Proposed Approach

The research project introduces an advanced approach to intelligent street lighting management, leveraging deep learning models for adaptive and scalable solutions. Unlike traditional rule-based methods, our models use real data to predict optimal lighting based on factors like traffic and weather.

A key feature is the integration of computer vision via the YOLOv8 algorithm for accurate vehicle detection, combined with cloud data from an LDR sensor. This enhances environmental understanding for better lighting predictions. The decentralized system, using MQTT for communication between vehicle detection and a Raspberry Pi controlling the lights, reduces bandwidth and infrastructure costs, while improving energy efficiency. Additionally, the system dynamically adjusts light intensity based on actual needs, conserving energy and extending bulb life.

4 Tools and Technologies Used

In this section, we present in detail the various tools, technologies and components we have integrated to develop our approach. Each of these elements has been selected for its essential role in the smooth running and efficiency of the overall system. We'll explain the specific features of each technology, as well as their contribution to our solution, including the use of YOLOv8 for object detection, MQTT for communication, and the Raspberry Pi as the central processing platform.

4.1 Deep Learning

Deep learning, a branch of machine learning, is inspired by the workings of the human brain to process complex data. It uses artificial neural networks composed of multiple layers of interconnected neurons. During training, these networks adjust the weights of connections to minimize the error between predictions and actual results, thus learning to recognize complex patterns in data.

In this project, a deep neural network is trained to predict the optimal duty cycle for street lighting control as a function of the number of vehicles detected and the cloud cover rate. The model learns to establish complex relationships between these inputs and the expected output.

Models based on deep learning have the advantage of automatically detecting complex patterns in data without the need for explicit modeling. They are versatile and adaptable to various types of data. However, they require large amounts of annotated data and significant computing power, and their decision-making process often remains difficult to interpret.

The use of deep learning in this project enables the development of a more intelligent and adaptive public lighting management model, based on traffic data and weather conditions, to improve the system's energy efficiency.

4.2 Computer vision and image processing

Computer vision, a field of artificial intelligence, aims to reproduce human visual perception to understand and analyze digital images and videos. One of the main challenges is object detection, which involves identifying and locating specific objects in images or videos, essential for applications such as surveillance and robotics.

In this project, the YOLOv8 (You Only Look Once version 8) algorithm is used for vehicle detection and counting. YOLOv8, an evolution of the YOLO architecture, is renowned for its real-time speed and accuracy. It divides the image into a grid and treats detection as a regression problem, simultaneously predicting bounding boxes and class probabilities without resorting to region-of- interest proposals, thus saving computation time.

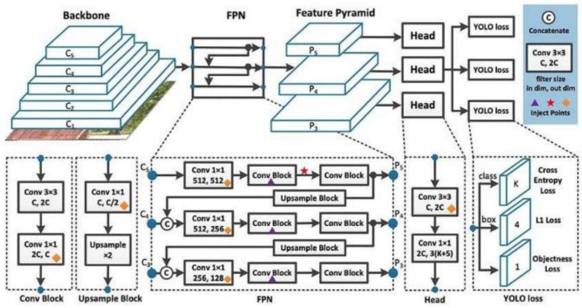

Fig. 1. YOLOv8 diagram

YOLOv8 offers improved accuracy, efficiency and the ability to detect objects of various sizes, based on recent advances in neural network architectures. In this project, vehicles detected with YOLOv8, combined with cloud measurements, are used as input to the deep learning model to optimize the street lighting duty cycle.

The use of YOLOv8 ensures accurate and rapid vehicle detection, facilitating its integration into a complete computer vision pipeline.

4.3 Wireless communication

Wireless communication enables the exchange of information without physical cables, using radio or infrared signals. In this project, the MQTT (Message Queuing Telemetry Transport) protocol is used to transmit data between a computer detecting vehicles and a Raspberry Pi controlling street lighting.

Lightweight and designed for machine-to-machine (M2M) communications, MQTT operates on a public/subscriber model, with a central broker distributing messages. The computer publishes the detection data, and the Raspberry Pi, which subscribes to this information, uses it to adjust the lighting. In return, the Raspberry Pi can send reports to the computer.

MQTT is advantageous for its low bandwidth consumption, reliability and suitability for unstable networks and low-power devices like the Raspberry Pi. This enables efficient and flexible communication for the project.

4.4 Embedded system

Embedded systems are specialized electronic devices, integrating hardware and software for specific tasks, often designed to be compact and energy-efficient. The Raspberry Pi, a low-cost single-board nano-computer developed by the Raspberry Pi Foundation, is very popular for electronic and computing projects thanks to its computing and connectivity capabilities despite its small size.

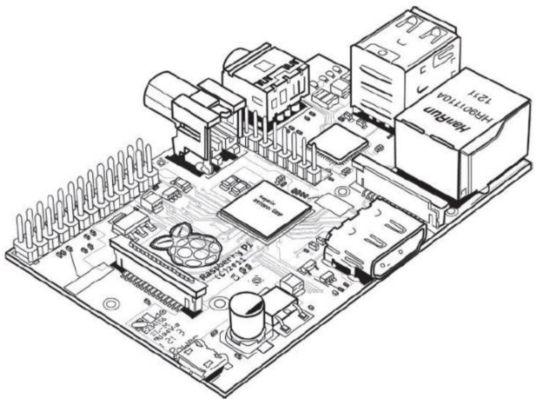

Fig. 2. Raspberry pi diagram

In this project, the Raspberry Pi is used to run a deep learning model. Although less powerful than a desktop computer, it can run lightweight, optimized AI models. Using the Raspberry Pi allows processing to be decentralized, bringing AI closer to data sources and reducing bandwidth requirements. This direct integration offers an autonomous, robust and energy-efficient solution.

However, the Raspberry Pi's limited resources may restrict the complexity of the models deployed, and optimizing them for embedded architectures may require further adjustments. In this project, the Raspberry Pi receives data via MQTT, performs the necessary calculations, and transmits the results to the street lighting control system, thus integrating AI in an efficient way that is adapted to the project's constraints.

4.5 Data acquisition

Data acquisition is essential for control and automation systems. It involves gathering information via sensors or instruments to guide decisions and processes. In this project, it provides the data needed for a deep learning model to predict the duty cycle of street lighting, including the number of vehicles detected and the cloud cover rate.

The cloudiness rate is measured by an LDR (Light Dependent Resistor) sensor, whose resistance varies with light intensity. This sensor is connected to the Raspberry Pi, which uses matching circuits and analog-to-digital converters to read and process the data. A specific program converts resistance into luminosity and estimates the cloud cover rate.

Data acquisition makes it possible to gather information in real time, facilitating more appropriate decisions. However, it can present challenges such as sensor noise and measurement errors. The LDR sensor, combined with vehicle detection, provides essential data for intelligent street lighting management in this project.

4.6 System control and command

System monitoring and control are essential for the precise regulation of various processes. In this project, these principles are applied to intelligently manage street lighting according to traffic flow and cloud cover. A key aspect is the generation of duty cycles, which determine how long a signal is active, thus regulating the light intensity of the bulbs.

The deep learning model predicts the optimum duty cycle based on the number of vehicles and the measured cloud cover. This ratio is transmitted to the street lighting control system via MQTT, which converts it into a control signal for the bulbs, using techniques such as pulse width modulation (PWM).

Lighting based on a variable duty cycle allows light to be adjusted according to actual needs, avoiding energy wastage and extending bulb life. However, flicker must be avoided, and rapid response to changing conditions must be guaranteed. This approach illustrates the integration of AI, data acquisition, wireless communication and embedded control systems in this innovative project.

5 Implementation

In this section, we explain in detail the process of implementing our solution. We describe each stage of development, the various tests carried out to ensure its smooth operation, as well as the challenges encountered and the solutions implemented to overcome them.

5.1 System design

The design of our overall system architecture is based on the integration of two main components: the prediction model based on artificial intelligence, and the Raspberry Pi embedded system for bulb control.

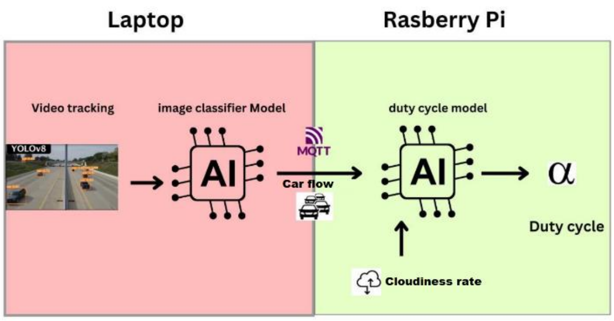

Fig. 3. System design diagram

5.2 AI prediction model

The predictive model is an essential component of our system, designed to anticipate and proactively adjust the light intensity of bulbs according to environmental conditions and traffic flow. Its development involved a methodical approach, integrating varied data and a rigorous training process. The training process began with the careful collection and preparation of data, including the number of cars detected, the measured cloudiness rate and the corresponding lighting power. This data was annotated and processed to meet the requirements of the model. After selecting a suitable neural network architecture, we began training the model using optimization and regularization techniques to minimize prediction errors and ensure good generalization. Once the model had been trained on a PC, it was deployed and integrated on the Raspberry Pi. Using real-time data on the number of cars detected and the rate of cloud cover, the model generates accurate predictions of lighting requirements. These predictions are then transmitted to the control system, which adjusts the chopper accordingly, enabling the system to react dynamically to environmental changes to ensure optimal lighting, efficient energy use, and user safety and comfort.

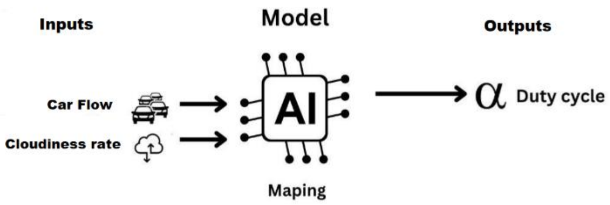

Fig. 4. AI model architecture

5.3 Embedded system on Raspberry Pi

The Raspberry Pi plays a central role in our system, acting as an embedded brain that coordinates various functionalities and makes real-time decisions based on received information. To detect and count the number of cars on the road, a PC runs YOLOv8, a real-time object detection model that analyzes video feeds from surveillance cameras and identifies vehicles. The counting information is then sent to the Raspberry Pi via the MQTT protocol, ensuring fast and reliable communication. Another key factor taken into account is the cloud cover, measured by an LDR (Light Dependent Resistor) sensor integrated into the system. This sensor detects the ambient light intensity, which varies depending on cloud cover: the cloudier the sky, the higher the resistance of the sensor, indicating a drop in natural light. The cloud cover and traffic data feed into a deep learning model, trained to determine the optimal duty cycle of streetlight bulbs based on environmental conditions.

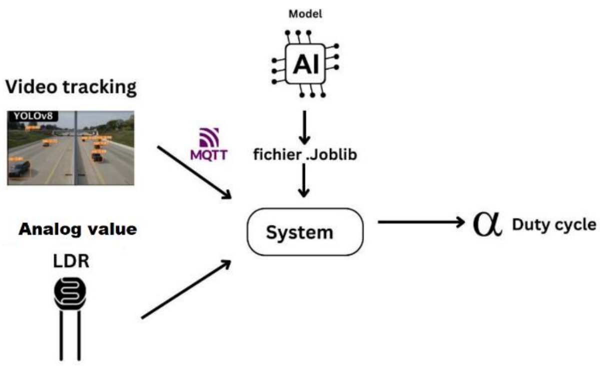

Fig. 5. Embedded system diagram

This system dynamically adjusts the light intensity to compensate for variations in natural brightness due to weather conditions, ensuring adequate lighting on the roads while optimizing energy efficiency. The Raspberry Pi uses the predictive model to calculate the ideal duty cycle of the bulbs, regulated by an electronic dimmer, ensuring public lighting that is effective, safe, and energy-saving.

6 Experimentation and Results

This section validates our innovative methodological approach through rigorous experimentation. We describe the experimental protocol, the data, the configuration parameters, and the evaluation metrics to ensure the reproducibility of the results. Then, the performance of our system in predicting the optimal duty cycle ratio, adjusting lighting intensity, and saving energy is presented through tables and graphs. Finally, an in-depth analysis highlights the strengths and limitations of our solution, its contributions, and improvement perspectives, thus demonstrating its effectiveness for smart public lighting management.

6.1 Experimental protocol

To evaluate the performance and validity of our intelligent public lighting management approach, we developed a rigorous experimental protocol aimed at replicating realistic conditions of road traffic and variations in sunlight while ensuring the reliability and reproducibility of the results. A simulated urban area was recreated in the laboratory, including a road model equipped with individually controllable LED streetlights, high-resolution cameras to capture video streams of the simulated traffic, and a sunlight simulation system using adjustable light sources and an LDR sensor to measure ambient light intensity. Pre-recorded video sequences reproducing various traffic situations and cloud scenarios were used as input data. The deep learning model was trained on a large dataset covering different combinations of traffic and cloudiness, while the YOLOv8 algorithm was optimized to maximize the accuracy and speed of vehicle detection. An MQTT communication system was implemented to ensure smooth data transmission between the different components. The evaluation metrics included the accuracy of the prediction of the optimal duty cycle, the dynamic adjustment of lighting intensity based on traffic and cloud variations, as well as the system's energy consumption. These performances were compared to those of a traditional lighting system, revealing potential energy savings. Various combinations of traffic and cloudiness were tested, and reproducibility tests were conducted to ensure the reliability of the results. This protocol allowed us to systematically evaluate the performance of our solution under controlled but realistic conditions, with the results and their detailed analysis presented in the following sections.

6.2 Obtained results

Figure 6 shows extracts from video streams captured during the experiments, illustrating our system's ability to detect and react to traffic variations in real time. This visualization provides a visual overview of the system's performance, enabling traffic fluctuations to be clearly identified in a variety of contexts, from peaks of activity to periods of moderate or light traffic, which is essential for effective management. In addition, the system's responsiveness is highlighted by the adjustments observed in traffic flow or traffic light management in response to these variations. Finally, these video extracts validate the system's effectiveness by enabling the accuracy of measures such as vehicle detection, traffic classification and intersection management to be assessed, thus reinforcing confidence in its performance.

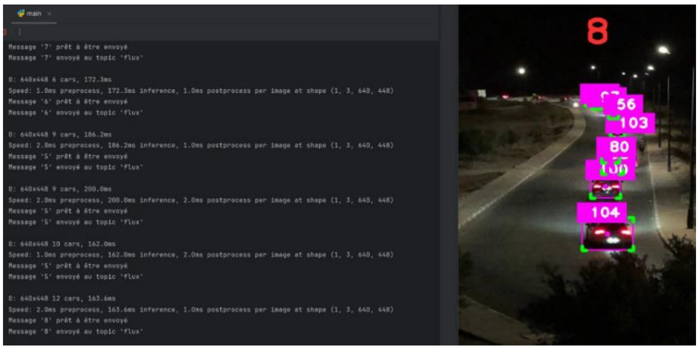

Fig. 6. Video stream capture

Table 1 illustrates the impact of random variations in road flow and cloud cover on the output of the street lighting system. The table highlights how the duty cycle, generated by the Raspberry Pi board, adjusts in response to these variations. In concrete terms, when road flow and cloud cover are low, the duty cycle decreases, leading to a reduction in the power supplied to the streetlights. Conversely, if traffic flow and cloud cover increase, the duty cycle rises, leading to an increase in power supply. This makes it possible to modulate light intensity according to actual conditions, thus optimizing the energy efficiency of the lighting network.

Table 1. Input and output values used in testing the system

Road flow	Cloudiness (%)	Duty cycle (alpha)	Electrical Power(W)
1,8776	45,6816	0,091744736	22,01874
3,2169	97,4256	0,34746173	83,39082
8,9219	29,1665	0,262877584	63,09062
9,6163	0,4942	0,005499869	1,319969
2,5573	89,8741	0,259048671	62,17168
4,1754	38,2289	0,156113774	37,46731

Figure 7 illustrates the entire lighting network prototype in detail, clearly showing the various components used in its realization, including sensors, controllers, communication modules, and power and lighting devices. Each element is carefully integrated to demonstrate the overall operation of the system.

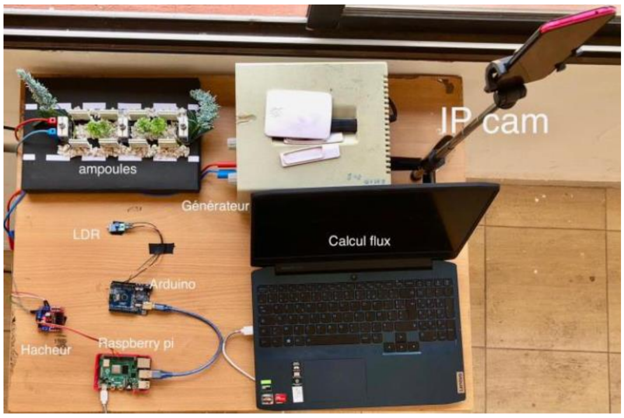

Fig. 7. Real system image

7 Conclusion

In short, this project successfully illustrates the impact of advanced technologies on the management of street lighting in modern urban environments. By integrating computer vision, the Internet of Things (IoT) and deep neural networks, an intelligent system has been developed to meet today's energy and environmental challenges. Using the YOLOv8 object detection algorithm, the system analyzes road traffic density in real time, while a photosensitive LDR sensor, connected to a Raspberry Pi module, measures weather conditions. The traffic density data is transmitted via the MQTT protocol and processed by a deep neural network model, which predicts the optimal operating cycle of the street lamps, taking into account light and traffic conditions. Experiments have shown that this approach delivers significant energy savings without compromising user safety, while reducing the carbon footprint. In addition, the use of artificial intelligence-based technologies offers greater flexibility and adaptability, contributing to the creation of more sustainable and resilient cities. Ultimately, this project marks a major step towards more intelligent and eco-responsible management of urban infrastructures, combining technology and sustainability for a harmonious future.

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