Sensors in public lighting

László Balázs[1], Ákos Horváth[2], József Nádas[3], György Molnár[3,4]

[1]Hungarian University of Agriculture and Life Sciences, Páter Károly 1, 2100 Gödöllő, Hungary,

[2]HUN-REN Centre for Energy Research, Konkoly-Thege Miklós 29-33, 1121 Budapest, Hungary,

[3]Óbuda University, Kandó Kálmán Faculty of Electrical Engineering, Tavaszmező 15-17, 1084 Budapest, Hungary,

[4]Széchenyi University Apáczai Csere János Faculty of Humanities, Education and Social Sciences, Liszt Ferenc utca 42, Győr, Hungary,

E-mails: balazs.laszlo@uni-mate.hu, horvath.akos@ek.hun-ren.hu, nadas.jozsef@kvk.uni-obuda.hu, molnar.gyorgy@uni-obuda.hu

Abstract: In smart cities, traditional infrastructure is combined with sensors and communication networks to improve the efficiency of communal services. Smart city solutions are often built on the public lighting network. Light poles offer an ideal place for sensors and controllers to monitor traffic and the level of air and noise pollution in the streets. We compare two trends of sensor-lighting integration: remote and local sensor data processing. Current communication networks enable the high-speed processing of the video signals streamed by surveillance cameras and the quasi-real-time identification of traffic players. Central processing of raw sensor data, however, raises privacy concerns. We argue that local signal processing adjacent to the sensor can be a cost-effective smart solution for municipalities. We show that simple hardware and low computation power are sufficient to determine the volume and the direction of traffic. The solution eliminates privacy concerns and provides adequate information for lighting controls and security alerts. Street light integrated anonymous sensors create a new value proposition for municipalities interested in affordable, future-proof smart lighting solutions.

Keywords: lighting controls; smart city; DALI; traffic monitoring; camera sensor

1 Introduction

From the beginning, the smart city solutions have been based on the street lighting network being the foundation of the smart city infrastructure [1]. The lamp posts provide an ideal location for sensors that monitor city life and can be powered by the lighting network. Another argument for linking urban sensors to the lighting network is the shift in lighting technology that started 20 years ago. As the luminous efficacy of LED lighting has improved and luminaires have become more affordable, energy retrofit programs have been launched worldwide to replace gas discharge lamps on lamp posts with LED luminaires [2]. It seemed appropriate to combine energy efficiency considerations with the digital transformation of urban infrastructure and extend the functionality of lamp posts. Adaptive lighting systems controlled by traffic sensors provided another argument for combining lighting and sensor networks. Intelligent lighting systems link traffic sensors and luminaires with communication modules into a data communication network. From there, it is only a step forward to adding sensors to the network whose signal is used not for lighting but for other elements of the urban infrastructure.

On top of the advantages of linking smart city solutions with public lighting, there are also barriers to spreading this new technological innovation. The design, installation, and operation of communication and lighting networks require different skill sets and have different economies of scale [3]. Monitoring and maintenance requirements are more complex in the case of communication networks. A convergence between the two technologies can be seen in integrated systems deployed in large cities. At the same time, smaller municipalities are discouraged from smart city developments because of the high investment and operational costs.

From a marketing point of view, smart city concepts are technology-push projects emerging from the technical community. There are several options for implementing a smart system; therefore, many unique technical solutions are available in the market. A start-up company with a good idea can come up with a large-scale ‘internet-of-things’ solution in a short time. For municipalities, the variety of technical options is bewildering. There is a wide range of technical solutions on the market, but once the particular system to be deployed has been selected, the municipality is bound to the chosen supplier with long-term operation and maintenance contracts.

The pressing need for interchangeability and maintainability has spurred device manufacturers to expand lighting standards. These standards, developed in collaboration between DiiA (Digital Illumination Interface Alliance) [4], the driving force behind the DALI system [5], and the Zhaga consortium [6], which is standardizing mechanical interfaces for lighting equipment, facilitate the connection of sensors, control modules, and wireless communication units to street lighting luminaires. This standardized interface ensures a future-proof solution and provides flexibility for the user, instilling a sense of reliability and reassurance about the technology's adaptability.

The goal of this study is to provide an overview of the current status of smart streetlighting solutions and assess the feasibility of integrating IoT technologies into economically sustainable development models aligned with the operational, financial, and functional needs of small municipalities and industrial parks. This article summarizes recent changes in lighting standards and presents examples of integrating traffic sensors and luminaires. We then show the results of our experiments utilizing a camera sensor to demonstrate the potential of simple algorithms in traffic monitoring. We discuss the benefits of simple autonomous luminaire control to municipalities, considering general data protection regulation compliance, reliability, and future-proofing of the technology.

2 Smart street lighting as a data platform

In the first smart street lighting projects, sensors and communication units were mounted directly on the lamp posts [7]. Even today, this is the simplest way to extend the functionality of the lighting infrastructure. Broadband data transmission using 4G/5G stations, WiFi hotspots, surveillance cameras, and air quality sensors can be installed next to the communication module [8]. The smart lamp post is now a special category in the product range of lighting device companies. The example shown in Figure 1 is popular on the roads of the mushrooming modern Asian cities. Still, there are also many other shapes and sizes of lamp posts with new features for lighting pedestrian zones, cycle paths, public spaces, and modern or historic streets.

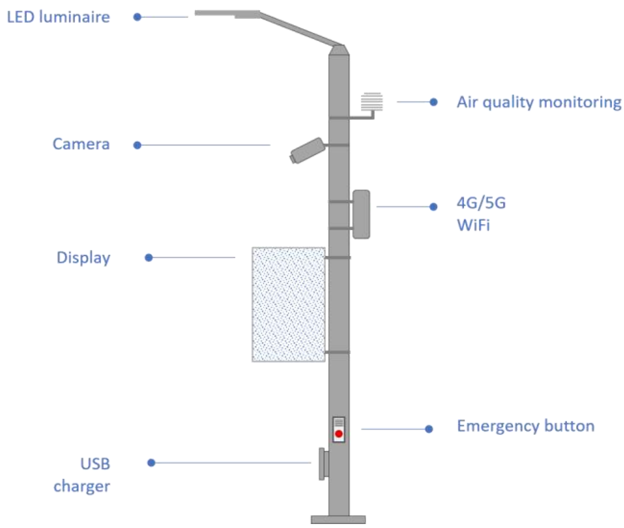

Figure 1

An example for a smart light pole

In addition to collecting environmental data, a useful service for citizens is a USB charger on the lamp post or a socket for charging an electric vehicle if the load capacity of the electricity network allows it. The pole is often equipped with a large emergency button directly connected to the police, ambulance, or fire brigades. A built-in microphone and speaker provide emergency phone functionality to the lamp post.

Sensors monitoring particulate matter concentrations, CO, CO_2, and nitrogen oxides provide important information on urban air quality. Air pollution has been monitored in large cities for a long time. The novelty of smart city systems is that air quality parameters are measured not only at one or two typical junctions but along the entire road network. The air quality map created from the data of the city-wide sensor network can be used to reduce air pollution, optimize traffic flow, or assess the impact of planned constructions [8].

Measuring noise pollution at high spatial resolution is also useful for urban planners. Continuously measured noise pollution at high spatial resolution provides much more reliable information about the state of the city than snapshots taken from a moving vehicle.

2.1 Broadband data transmission

In the smart light pole concept, large amounts of data are transmitted via broadband communication networks to servers that process the raw sensor data. It is no coincidence that telecommunication companies specializing in data generation, transmission, and processing are at the forefront of deploying and operating smart city sensor networks. The operation of smart city infrastructure is regarded as a new revenue stream. Real-time data about traffic flow and people's preferred routes in the physical space are the most valuable assets with intrinsic value. Information on urban traffic, parking habits, noise, and air pollution is not only of interest to the city but also of significant value to property developers, shopping centers, insurance companies, and marketing agencies.

Market analyses show growing interest among all stakeholders in smart street lighting solutions, but municipalities are reluctant to take radical steps towards transforming traditional street lighting into a smart data platform.

A study by the Massachusetts Institute of Technology [9] highlights that companies specializing in operating and maintaining public lighting networks lack the skills to operate smart systems. This knowledge gap is the primary barrier to the adoption of innovative solutions. The primary objective of local authorities is to improve the service to the local citizens and reduce the cost of street lighting. From the city's point of view, it is preferable to improve the lighting network step-by-step rather than risk a radical overhaul of the operation. Moreover, the benefits of the new services do not necessarily accrue to the municipality.

Cameras and microphones in public spaces raise concerns about violating privacy rights, the second most important barrier to spreading smart city solutions [10]. Images of surveillance cameras are primarily used for traffic counting and classification of vehicles [10-12]. On the other hand, image sensors have sufficient resolution for complex object detection [13], or identifying other personal information, like a vehicle's license plate [14]. Microphones record noise levels in the streets to assess the traffic volume [15], but advanced technologies enable the recognition of whispered speech from noisy audio signals [16, 17]. Data collected by a dense sensor network can be useful in improving the quality of life in a city. On the other hand, the ambiguity of data ownership and the lack of transparency in handling data raises privacy concerns [9, 18-21]. There is a growing interest in technical solutions that eliminate or overcome the bottlenecks of spreading smart city solutions.

2.2 Local data processing

A possible approach to mitigating privacy concerns is to process data locally rather than aggregating all raw sensor data in a centralized database. Recent advancements in edge computing and distributed data processing, along with updated lighting standards that facilitate the integration of sensors and controllers into street lighting luminaires, offer new opportunities for developing intelligent lighting solutions.

2.2.1 Edge computing

Edge computing [22] plays an important role in smart lighting systems enabling data processing and decision making to occur in the luminaire rather than relying on a centralized cloud platform. Edge computing reduces latency, allows fast responses to adapt the streetlighting to actual traffic needs. On the other hand, it enhances data privacy through localized processing of sensor data. A key advantage of using edge computing in smart streetlighting systems is the scalability [23]. Scalability applies to both the functionality and deployment of the system. The sensors, microcontrollers are integrated into a scalable IoT system [24]. The number of IoT devices can be increased gradually in a properly managed hardware-software codesign process. On the other hand, the functionality of the IoT network can also be extended beyond lighting controls by implementing new sensor types into the luminaires. Although edge computing reduces network latency, systems without cloud computing increase the computational latency of the edge devices [25]. Increasing computational power in the luminaires increases system cost and power consumption. Hybrid architectures combining the advantages of edge computing and centralized cloud systems provide a possible solution for the optimization of costs and functionalities [25, 26].

2.2.2 Lighting standards enabling sensor-luminaire integration

In smart streetlighting systems sensor data are used to identify the actual traffic condition in the vicinity of the lightpole and adjust the luminaire's power to meet the requirements of the lighting regulations. In our approach each sensor in the network is connected to a microprocessor. The microprocessor selects the signal features required only for public service. For example, by analyzing a camera image, the vehicle type and the time of passing are determined; this is the only information that will be stored locally. The traffic volume (number of vehicles per hour) broken down into vehicle types can be determined by accumulating stored data. This is sufficient information to adjust the power of street lights to the actual traffic needs enabled by road lighting standards [27-29]. Adaptive control reduces the energy consumption of public lighting. Another cost-saving factor is the low bandwidth required to transfer processed signal data via the communication network relative to the needs of large data platforms.

Recent advancements in lighting_standards support the development of sensor-integrated smart luminaires [30-32].

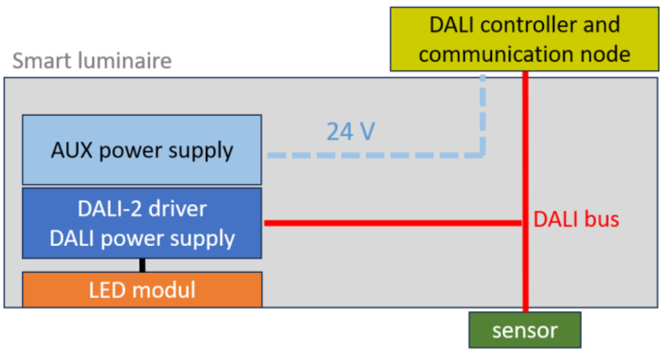

Figure 2
Layout of D4i compatible smart luminaires

The Zhaga consortium and the Digital Illumination Interface Alliance (DiiA) jointly developed the *de facto* standards for smart street lights. The Zhaga (book 18) sockets enable plug-and-play interoperability of sensors and communication nodes. The D4i specifications support the wireless connectivity of smart LED luminaires.

Figure 2 shows a potential configuration of smart luminaires. The LED driver and the sensor secured at the bottom of the luminaire rely on the DALI bus to communicate with the controller. The DALI controller with the communication node is positioned atop the luminaire. Zhage Book 18 sensors are shown in Figure 3, and a smart LED luminaire equipped with a communication node and controller is depicted in Figure 4.

Figure 3
Zhaga Book 18 compatible sensors for smart street lighting applications. a)TE Connectivity LUMAWISE Motion Sensor [33]; b) Tridonic Sensor X camera sensor [34]; c) Signify LRI8135/00 radar sensor [35]; d) Citylight CNODE IOT AMR [36]

Sensors of different sizes and complexity can be connected to the LED luminaires. Figures 3 a) and b) show an infrared motion sensor and a camera sensor that are usually secured at the bottom of the luminaire. Larger housings in Figures 3c) and d) incorporate the communication node and set of sensors, including a traffic monitoring radar.

Figure 4
Smart LED street light equipped with a Zhaga Book 18 controller and communication node

The DALI bus inherently limits the data transfer rate between the sensor and the controller (Figure 2). Therefore, raw sensor data processing should occur adjacent to the sensor. For an affordable smart solution, we need to consider several constraints on the sensor and processor: size, power consumption, reliability, and cost. In the following, we demonstrate the capabilities of a low-cost camera module for use as a traffic counting and classification sensor.

3 Materials and Methods

3.1 The experimental setup

In our experiments, we did not build a full-fledged smart luminaire with DALI communication. We restricted our study to creating a simple IoT system incorporating an ESP32-CAM camera module and a Raspberry Pi server (Figure 5). The ESP32-CAM is among the cheapest camera sensors providing an image resolution sufficient to demonstrate feasibility of traffic detection algorithms. The Raspberry architecture is widely used in IoT studies as a server aggregating data from the nodes and capable running complex analytics. This configuration was a model for sensor data processing, intra-luminaire communication, and wireless data transfer from the communication node to a central data server.

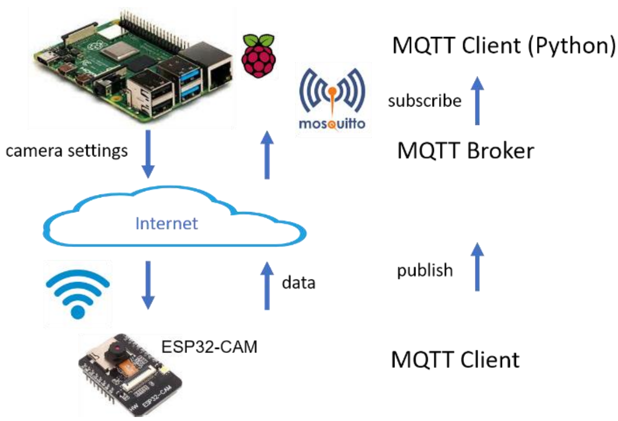

Figure 5
Experimental setup using ESP32-CAM camera sensor. Images were processed locally by the ESP32 microcontroller. Only 12 numbers were transferred to the Raspberry Pi server using the MQTT protocol.

3.2 The IoT hardware

The ESP32-CAM model incorporated an OV2640 RGB camera with a maximum resolution of 1600×1200 pixels. In our experiments, the camera's resolution was limited to 240×176 pixels. This resolution was sufficient to detect pedestrians and vehicles beneath the luminaire. 8-bit grayscale images were captured with 1 one-second repetition time. The Arduino IDE was used to write and upload the C code to the ESP32 microprocessor. The output of the image processing was an array of 12 characters. This array was sent to a server using the MQTT protocol. The MQTT broker (Mosquitto) was running on the Raspberry server. The MQTT clients were the ESP32-CAM module publishing the array of 12 characters and a Python program also running on the Raspberry, which was the subscriber to the topic on which the image analysis results were published. The ESP32-CAM used WiFi to connect to the internet. The Raspberry Pi got a fixed IP address, allowing remote access to the server. Modem connecting of the Raspberry Pi to the high-speed internet was also reconfigured to allow MQTT and SSH commands to be transferred remotely. During the field tests, the ESP32-CAM was powered by a 5V USB power bank.

3.3 Image processing algorithm

In our experiments, we employed very simple calculations that do not require knowledge of sophisticated image processing methods, such as segmentation, background substruction, or object detection.

The camera image of 240×176 pixels was subdivided into a 3×4 matrix. One topic in the MQTT communication was reserved for the average gray values of these 12 pixels. Object identification is impossible at such a low resolution, but the average gray values still provide valuable information about the movements in the camera's view field.

We also calculated gray value differences between adjacent images. An image was represented by an array of $n = 42\,240$ pixels. The value of one pixel (p_i) was between 0 and 255. The difference array ***d*** was calculated by subtracting the previous pixel value $p_{i,t-1}$, from the actual pixel value $p_{i,t}$ in Eq (1). The standard deviation of gray value differences in Eq (2) was a powerful metric to highlight the changes in the scene observed by the camera.

$$d_i = p_{i,t} - p_{i,t-1} \tag{1}$$

$$SD_i = \frac{\sum_{i=1}^{n} d_i^2}{n-1} \tag{2}$$

4 Results and Discussion

The algorithm was tested in the laboratory and in the streets under real traffic conditions. First, we present the results of some laboratory tests to demonstrate the working principle of the image processing method.

4.1 Laboratory tests

The camera was taking pictures from a computer monitor. The image on the monitor consisted of four quadrants: one black, one gray, and two white rectangles, as shown in Figure 6. The yellow grid in Figures 6a)-d) represents the 3×4 Sectors used in the image analysis.

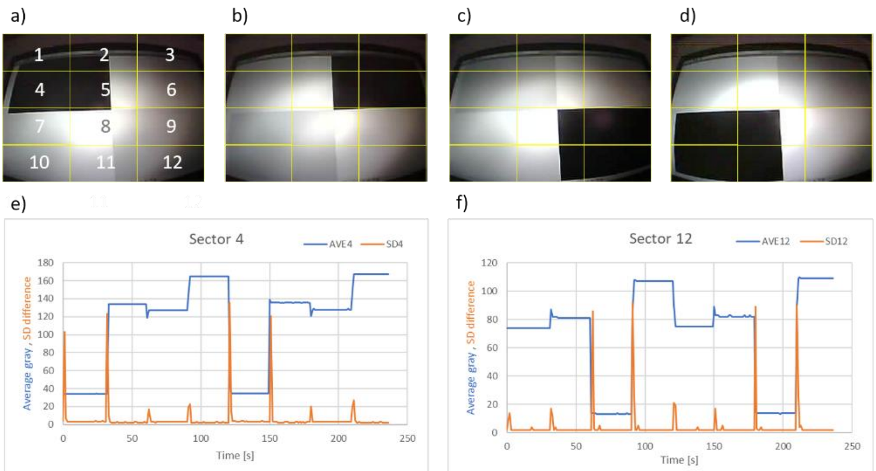

Figure 6

Successive image changes in a 30-second cycle (a-d) were used to test the camera and the image processing algorithm. The average gray values (blue line) and the standard deviation of the gray value differences between successive images (orange lines) are shown for sectors 4 (e) and 12 (f).

The numbers identifying each sector are depicted in Figure 6a). The image on the monitor was rotated clockwise every 30 minutes in the order of a), b), c), and d). Otherwise, the scenario was constant in front of the camera. Figures 6e) and f) also show the average gray values (blue line) and the standard deviation of gray value differences (orange lines) as a function of time for Sectors 4 and 12. The starting time corresponds to the scenario in Figure 6a). Sector 4 is black initially, reflected by a gray value of less than 40. Sector 12 is in the gray zone with a gray value of 77. In the next step, shown in Figure 6b), Sector 4 is in the white area with a gray value close to 140. In the third step (Figure 6c), Sector 4 is still bright with a slightly lower gray value than in the previous case. Sector 12 became black, as reflected by the drop in gray values between 60 and 90 seconds. The standard deviation of the difference gray values is a more powerful metric to highlight the occurrence of scenario change. The orange peaks indicate the time of scenario changes, whereas the peak height is characteristic of the absolute value of the differences. The SD curves are flat in the case of a constant scenario. The tiny peaks between the scenario changes correspond to ambient noise.

4.2 Field tests

Field tests were conducted on a service road of the KFKI Campus, Budapest, open to low-speed motorized traffic and pedestrians. The camera sensor was fixed beneath an LED luminaire with a downward view of the road surface. The mounting height was 3 m. The road width was 6 m. The camera captured an area of about 5 m × 5 m. In Figure 7a), we present the observations about pedestrian movement starting from Sector 1 toward Sector 3, as indicated by the white arrow. The person remained in the first stripe of the camera image during his 13 s walk as indicated by the changes in the SD values in various sectors.

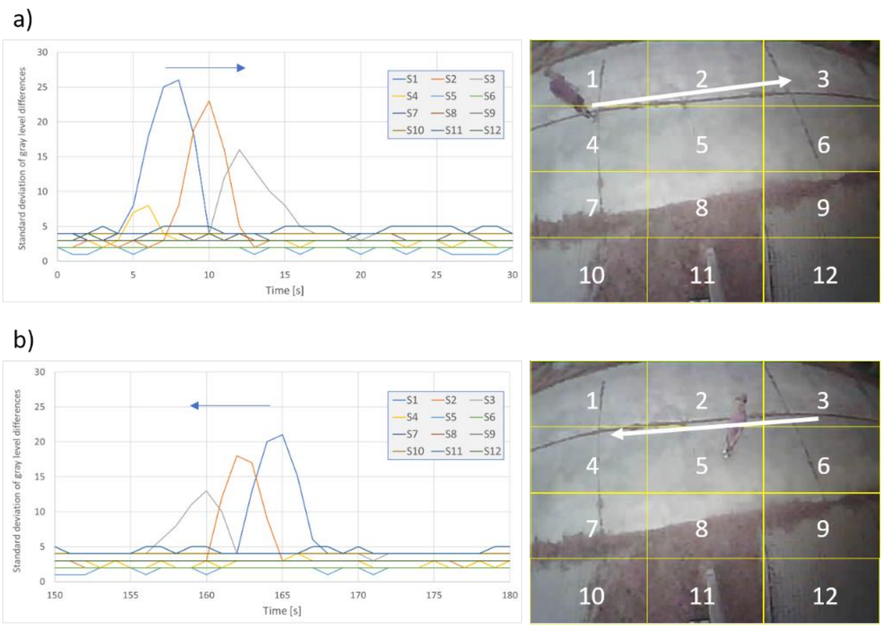

Figure 7

The standard deviation of the gray value differences between successive images. a) A pedestrian moving from Sector 1 toward Sector 3. b) A pedestrian walking from Sector 3 towards Sector 1.

The first blue peak corresponds to Sector 1 followed by Sectors 2 and 3. In the rest of the Sectors SD values remained at the noise level. Figure 7b) shows the walk in the opposite direction from right to left. Sector 3 is the first peak in Figure 7b) followed by Sector 2 and 1. In this scenario, the size of the pedestrian was on the scale of the size of a sector. The temporal profiles of SD values characterize the walk's direction, trajectory, and speed. The camera image analysis provides more information about the movement than a simple PIR motion sensor. We want to stress that the person's image was only shown as an illustration of the experiment. In the image processing algorithm, images are not stored; consequently, hints about the personal identity of the pedestrian cannot be retrieved.

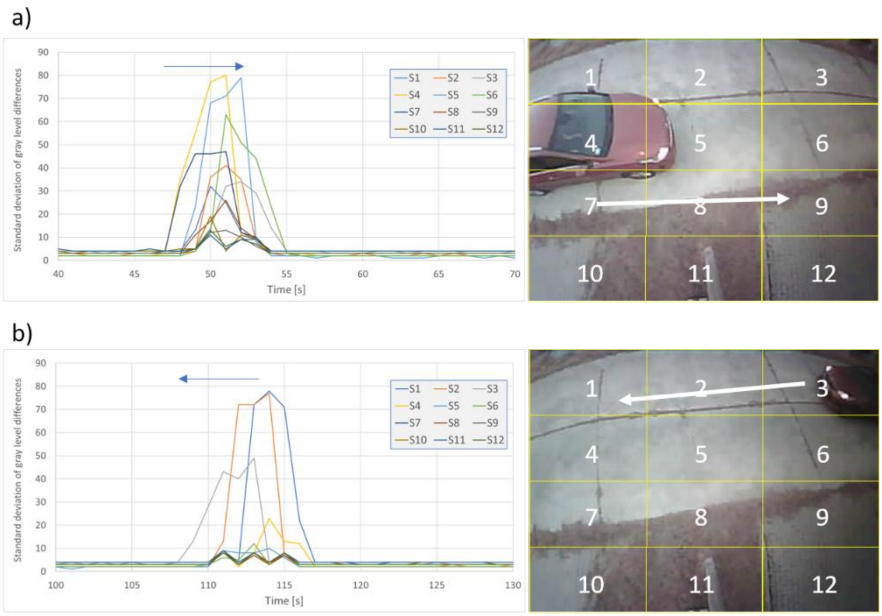

Figure 8

A car moving from a) left to right, b) from right to left.

Car movements generate larger signals compared with the presence of a pedestrian. Figure 8a) shows the standard deviation of gray value differences generated by a car moving from left to right. Figure 8b) demonstrates the measured features in the case of driving in the opposite direction. Since the size of the car is larger than one sector, more peaks can be seen in Figure 8 than in Figure 7. We can determine the vehicle's driving direction from the sequence of peaks. In Figure 8a) the first peaks correspond to Sectors 4 and 7, and the decay on the right-hand side is associated with Sector 6. In Figure 8b), the car appears in Sector 3 and leaves the image at Sectors 4 and 7.

4.3 Potential applications and future perspectives

Although our experiments used very simple hardware and software, the method described has several practical implications.

The low-cost camera module is a powerful sensor for traffic monitoring. Using the Zhaga Book 18 receptacles, the small, low-power consumption sensor can be easily connected to an LED luminaire. The image-processing software requires no prior information about the lighting conditions and background. Still, it is an effective tool for traffic flow characterization. The solution is anonymous since it does not collect personally sensitive data. The algorithm handles pixel level information only and decisions are based on the brightness distribution of individual pixels.

The microcontroller can send processed information to the DALI controller. The DALI controller can adjust the power of the LED luminaire according to the local traffic information and act as an autonomous device. The other option is for the luminaire to have a communication node and send local traffic information to a central controller. The central controller can optimize the light level of the connected luminaires in a more advanced adaptive lighting scheme.

In a more advanced setup, the microcontrollers can run object detection algorithms trained to detect additional traffic information, such as vehicle type, distinguishing between human and animal movement, or other traffic scenarios characteristic of the local environment. Applying advanced machine learning methods will be the scope of further investigations.

In adverse meteorological conditions, such as mist, fog, or heavy rain, glare from the road surface can limit the performance of camera sensors. A multisensor approach, using ultrasonic, infrared, or radar sensors, can increase detection reliability, but the system's cost and complexity will increase. Developers should find the appropriate trade-off between system performance, as well as investment and operating costs.

Information about traffic is also valuable for increasing safety and security in the streets. Traffic flow has characteristic SD patterns, and deviations from the normal signal trends can trigger alerts for security guards or police.

The simple algorithm has many advantages in education. Students with basic programming skills can be engaged early in developing smart lighting solutions. Students do not require complex knowledge about image processing and machine vision software. Training operators and maintenance personnel can also benefit from the simple visualization of scenarios evolving under the lighting equipment.

Finally, simple hardware and software address sustainability concerns about smart lighting. The knowledge gap between lighting network operators and top-notch data scientists will not disappear. Municipalities may prefer simple-to-learn and easy-to-operate working solutions rather than sophisticated, high-tech systems requiring well-paid engineering jobs.

Conclusions

High operation costs and privacy concerns are the two major barriers to adopting smart lighting solutions on a large scale. Municipalities are cautious of investing in a one-step jump from traditional lighting to the radically new concept of street lighting as a data platform. Recent advancements in lighting standards foster the integration of sensors into street lights, enabling a low-risk, step-by-step extension of lighting functionalities [37]. Our experiments demonstrated that a combination of a low-cost camera sensor built into a luminaire and a simple image processing algorithm could provide valuable information on the human and vehicle movements in the surroundings of the light pole. We presented a method that can detect the direction and the speed of motorized and non-motorized traffic without the possibility of retrieving personally sensitive information from the captured images. This approach eliminates privacy concerns and excludes the possibility of violating European GDPR regulations. The traffic data can be used for lighting controls and monitoring the neighborhood's safety and security conditions. The standardized solutions define new value propositions for municipalities interested in affordable, future-proof smart lighting solutions.

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