Smart Lighting Controller

Nelson Oliveira, MEEC, Instituto Superior Técnico

Abstract— The preservation of the environment and the price of energy are two of the main reasons that justify the importance of energy savings. To reduce energy consumption, new technologies and solutions were developed for different sectors. The lighting industry is one of the areas where great evolutions occur in terms of energy efficiency.

Lighting large spaces that do not have natural light, such as warehouses, underground parking, and corridors, can consume a lot of energy and become quite expensive. For these types of spaces, it is important to have technological solutions that reduce energy consumption while maintaining a good lighting quality.

In this context, a networked system with a decentralized architecture was developed. Each node of the network operates autonomously, responsible for detecting people, communicating with neighboring nodes and controlling the intensity of the lamp associated with it. Communicating with each other, each node will also have a function of estimating the path of people, illuminating trajectories in advance for greater comfort and safety.

A prototype was developed that allows energy savings that, in certain contexts, can reach 36% compared to traditional controls that turn on all the lights when a person is detected.

Keywords— Lighting controller; decentralized architecture; distributed network solution; energy efficiency.

I. INTRODUCTION

The lighting sector is a major energy consumer in buildings, accounting for around one third of energy consumption in commercial buildings and even more in office buildings [1]. To reduce this consumption without decreasing the comfort of the occupants, several technologies have been implemented in buildings, such as the use of economical LED lamps, light sensors, motion sensors, Daylight Harvesting and time scheduling systems.

Energy savings can be achieved by efficient lighting management. In houses, lighting management can be simple and there is not much room for savings, as the inhabitants are responsible for the electricity bill, so there is more care in consumption to avoid waste.

However, in public places or large buildings (garages, car parks, warehouses...) where you need regulated lighting requirements, energy saving in lighting can be more complex. And as in these places people are not responsible for turning off the lights, which results in negligent waste. With the use of sensors, actuators and a central system that controls them, it’s possible to carry out an efficient lighting management, where only places where people are present are lit. An ideal algorithm for controlling the luminaires will depend on several factors, such as, there may be areas in the place that need to be always lit and others only when they detect people; scheduled lighting; or even lighting that adapts its intensity depending on the time of day to take advantage of natural light. By implementing an adequate management system, it’s possible to reduce energy consumption and allow comfortable and efficient lighting of the space.

It’s possible to reduce lighting energy consumption by regulating the intensity of the lamps and taking advantage of outdoor lighting if the site has windows, a technique known as Daylight Harvesting. Using light sensors and motion detectors, it’s possible to define a lighting intensity in spaces where people are detected. This type of control is very common in offices and offices.

When lighting large spaces that do not have natural lighting (such as warehouses, garages/underground parks, and corridors) it’s usual to be permanently lit or have the classic timed switches or motion sensors installed. These options are not the most economical because they involve turning on the entire lighting of the space. In cases where there is an abundant movement of people, it can cause that lighting is always on.

This thesis aims to develop a fully distributed and modular approach, in which each node in the network operates autonomously without using a central unit. With distributed processing it’s possible to obtain a scalable solution applicable to larger systems.

Each node is responsible for detecting people, communicating with neighboring nodes and controlling the intensity of the lamp associated with it. Communicating with each other, each node will also have the function of predicting the path of people, illuminating their trajectories in advance. For example, a person moving in an open space and in a certain direction, the controller must predict this direction and will have to illuminate the areas that will be reached by this person. If there is a change of trajectory, nodes that were illuminated in advance and that do not detect presence will automatically switch off (or go back to their original state) after some time.

To test and evaluate the developed solution, a prototype consisting of 12 luminaries will be implemented, which allows 4x3 or 6x2 matrices, which enables a minimally realistic evaluation in different scenarios. To simulate detections events on the network, a gateway is used, this gateway is responsible for simulating detections and sending configurations. Each luminaire consists of a printed circuit board with an Arduino NANO (atmega328p), an nRF24L01+ radio module, buttons/switches, and LEDs.

II. STATE OF ART

Lighting systems in open-plan office spaces are most often addressed with the aim of saving energy.

To promote energy efficiency in the use of lighting, in addition to the use of more efficient luminaires such as LEDs, several lighting control strategies were designed and implemented in office buildings. Examples of such strategies include automatic daylight harvesting control, which consists of taking advantage of ambient light from outside through the building's windows; light intensity control and occupancy-based control. Implementing a light system with occupancy sensors is an economical and easy solution to reducing

Thesis summary to obtaining the master's degree in Electrical and Computer Engineering in July 2021.

Nelson Oliveira, Master's student in Electrical and Computer Engineering at the Instituto Superior Técnico (e-mail: nelsondacostaoliveira@gmail.com).
lighting energy use. This implementation has been successfully demonstrated in several studies, where the energy used for lighting was reduced between 20% and 60%, depending on the configuration, type of space and type of occupancy sensor used [2].

In offices, it’s important to have good lighting quality for better worker comfort considering energy efficiency. When choosing the controller, it’s necessary to consider the use of a single controller or combination of several types of controllers.

Car parks have never been the easiest areas to light efficiently. They are, of course, a potentially dangerous environment for drivers and pedestrians, which means that good visibility and safety are always a priority. Thus, it’s sometimes necessary to light the space 24 hours a day, seven days a week, leading to high energy use and increased costs. To provide a safety environment, GreenParking [3] is a low-maintenance wireless decentralized lighting system that also works perfectly as a modification/upgrade solution. In wireless communication, ZigBee technology is used for devices with low consumption and long transmission range. When pedestrians are detected, the zone in front is lit up to 100% to feel safe and comfortable. As the pedestrians leave a lighting zone, it’s set to a backlight level of 20% to save energy. The installation of this system in car parks resulted in energy savings of 50 to 84%.

In the approach of Eveliina Juntunen and colleagues [4], an intelligent street lighting system that illuminates pedestrian trajectories in just two directions was tested. This system consists of 28 lighting poles that have been adapted for this test, each pole is responsible for determining the direction and sending this information to a gateway, to then send the data to a server that controls the lighting. The received data and, most importantly, the direction of pedestrian movement is provided to a dynamic lighting control software – VirtuAUL. Thus, this system can be characterized as a centralized system. The energy saving of this system was 60-77% compared to the previous control, where the lamps are scheduled at 100% of their intensity when there is no sunlight. In comparison with this approach, the algorithm to developed will address the problem to implement a decentralized system that anticipates in more than two directions.

In the dissertation by Miguel Amado [5] a decentralized lighting system for large spaces without natural light is simulated. Each luminaire is responsible for detecting people, sharing information with neighboring luminaires and regulating the intensity of the lamps they control. Interacting with each other, the luminaires seek to predict the trajectory of people, illuminating it in advance for greater comfort and safety. The algorithm was simulated in a space composed of 100 luminaires, distributed in a 10x10 matrix. Comparing the performance with a traditional control, in which all the lighting is turned on when people are detected, it allowed to obtain energy savings of up to 74%, proving to be a very attractive solution for this type of spaces.

In comparison with the approach presented by Miguel Amado [5], the aim is to implement a physical system identical to the one simulated. However, the implementation of the system to be developed in this dissertation aims to improve some aspects of the simulated approach.

III. SOLUTION DESCRIPTION

A. Control Algorithm Description

In this dissertation, the implementation of a decentralized lighting control algorithm is proposed, to operate in large spaces. The aim is to develop a prototype consisting of a network of autonomous luminaires, which detect people and light up the space around them, anticipating the trajectory of people’s movement.

Each luminaire communicates with its neighbours to illuminate the surroundings where the detection took place and the information to anticipate the direction to be illuminated. This luminaires process information to make decisions, placing their lamps at a certain level of intensity.

The main feature is to illuminate the area around the location of people and the trajectory of their movement. For the lighting to be comfortable for the user, is followed the strategy of the lighting being gradually reduced as the distance increases towards the user. As represented in the fig. 1, where the dimensions are larger than the prototype to be developed. At the ends of the space, the luminaires can be configured to never switch off, maintaining a reduced intensity even if no presence is detected. The system also has the function of gradually changing the intensity of the lamps when there is a change of state, to avoid sudden changes in the lighting of the space.

In the implementation of a distributed system, each luminaire consists of a modular control unit. This decentralized architecture avoids the "bottleneck" effect in communication and processing associated with a centralized solution (the central unit is responsible for receiving and sending the messages to all nodes and supporting all necessary processing). In the proposed distributed system, it’s possible to have an unlimited number of nodes because communication and processing are performed locally (between a node and its neighbours).

In the implementation of a distributed system, each luminaire consists of a modular control unit. This decentralized architecture avoids the "bottleneck" effect in communication and processing associated with a centralized solution (the central unit is responsible for receiving and sending the messages to all nodes and supporting all necessary processing). In the proposed distributed system, it’s possible to have an unlimited number of nodes because communication and processing are performed locally (between a node and its neighbours).

B. Communication Between Nodes

Communication in the luminaire network is carried out in short-range broadcast, as it’s only intended to communicate with neighbouring nodes and not with nodes that are further away. In this way, the probability of collisions between the messages of the global system nodes is reduced, regardless of their size.

The origin of the message is analysed, and the luminaire makes the decision whether to continue processing or reject the message. Each luminaire rejects messages sent by luminaires that do not belong to its neighbourhood or outside its communication range.
The luminaires furthest away from the origin of the emitted message need to be aware of the presence to illuminate with a reduced intensity. Thus, the luminaires close to the detection source retransmit the messages. To avoid sending repeated messages, each luminaire rejects messages whose origin of the detection event coincides with the recipient's coordinates. And rejects messages whose origin of the message coincides with the origin of messages that were previously retransmitted. This avoids message cycles and reduces network traffic.

C. Lighting Patterns

The luminaires that light up the space can be configured with lighting patterns depending on the environment's preferences. Each luminaire lights its lamp with a certain intensity depending on its distance from the origin that detected a presence or anticipated a trajectory. In Fig. 2 some examples are presented, in which the distance between luminaires is calculated with the Euclidean distance. The High Radius (HR) is the distance for which the luminaires light up at high intensity, Medium Radius (MR) for luminaires that light up at medium intensity, and Low Radius (LR) for the more distant luminaires which light up at low intensity. The luminaires located with a distance between 0 and HR light up with high intensity, between HR and MR they light up with medium intensity and between MR and LR with low intensity.

D. Anticipation of Trajectories

When lighting the trajectories, it’s necessary to predict the direction of movement of people. It’s implemented that each luminaire will predict the trajectories based on the presences detected in its neighborhood occurring in a in a time interval.

A trajectory is determined through two neighboring luminaires. The luminaire that detects a presence analyzes the detections occurring in its neighborhood and decides which paths to illuminate. The directions of the trajectories are only 8, represented in Fig. 3.

The luminaire that detects presence alerts the neighboring luminaires to register the occurrence of the detection. When the person moves to one of the neighboring luminaires, it already has information on the person's previous location and anticipates the trajectory.

The range of the anticipation effect can be increased by using message propagation between luminaires. Luminaires that are in one direction relay information to anticipate lighting until the defined range is reached. The Anticipation Range (AR) variable is configured according to the user's preferences, which indicates the distance to be anticipated that illuminates with high intensity.

E. Detection Borders

In the movement of pedestrians, multiple detections can occur at the borders for just one person. As an example, detection can occur by only one luminaire, by two luminaires and by four luminaires.

Movements in the detection boundaries can result in multiple unwanted directions as exemplified in Fig. 4. In which the luminaire L23 detects presence and analyzes that detection occurred in L13, L14 and L24 and respectively anticipates the directions for L33, L32 and L22. And the same reasoning happens in L24 that anticipates directions in L34, L35 and L25. In this example the trajectories in directions to L22 and L25 are anticipated only one of them because the detection interval between L23 and L24 is short, if it was detected first in L23 and then in L24 then it’s anticipated towards L25, and in the case of detect L24 and then detect L23 is anticipated L22. So, there are five anticipated directions in which only two are correct.
Diagonal movements on the detection boundaries also result in multiple incorrect trajectories as shown in Fig. 5. When moving from L33 to L44, the pawn is detected by L34 and L43 which anticipate to L35, L53 and L25 or L52, when detecting in L44 (image from the right) is anticipated towards L45, L55 and L54. So, it’s anticipated in 6 directions where only one is correct.

For detections at borders, the algorithm must analyze the occurrences of detections in time and space and decide which trajectories to anticipate.

IV. ALGORITHM IMPLEMENTATION

A. Detection

In the developed prototype, the detection is activated through a switch or through a message sent via radio, which facilitates the development and testing of the algorithm. If the use of PIR sensors was chosen, the luminaires had to be spaced apart from each other, due to the overlapping of detection zones.

The detections generated by each luminaire are limited to one detection for each time interval, to reduce message traffic. In other words, when a luminaire detects a presence in its detection zone, then it can only detect a new presence after a stipulated period. This approach is known as debouncing, where the time of the warm standby period is in the order of seconds.

B. Radio Communication

In the implementation of the communication algorithm with the nRF24L01 module, the RF24-master library [6] is used. The nRF24L01 radio is initially configured with a maximum communication speed of 2 Mbps, to reduce message collisions. And the frequency of the communication channel is chosen in consideration of the channels occupied by the Wi-Fi Routers, to avoid interference, it was decided to choose the last channel 125 in nRF24L01 which corresponds to 2525 MHz.

The power amplifier is set to the minimum value of -18 dBm, to avoid long-range communication because the communication purpose is only in the neighborhood.

To activate the module’s Broadcast mode, the auto-acknowledgement is deactivated, so when a luminaire sends a message it does not need to receive confirmation of reception. The luminaire sends a message to all and only accept the ones that are in the neighboring, as shown in Fig. 50. The auto-acknowledgement is only active when it’s necessary to send the messages of individual configurations of the luminaire.

In the retransmission of messages by the luminaires that are in the

neighboring of the detection message collision occurs. When the luminaires receive the detection occurrence message, they all retransmit all at the same time, which can result in collision between them. Thus, the luminaires to be retransmitted will have to perform a random wait before sending the message.

The message information consisting of 10 bytes is described in Table I.

<table>
<thead>
<tr>
<th>Byte</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operation code</td>
</tr>
<tr>
<td>2</td>
<td>ID of the luminaire it detects</td>
</tr>
<tr>
<td>3</td>
<td>Sender’s x coordinate</td>
</tr>
<tr>
<td>4</td>
<td>Sender’s y coordinate</td>
</tr>
<tr>
<td>5</td>
<td>Coordinate x of the luminaire it detects</td>
</tr>
<tr>
<td>6</td>
<td>Coordinate y of the luminaire it detects</td>
</tr>
<tr>
<td>7</td>
<td>Coordinate x of the luminaire in anticipation</td>
</tr>
<tr>
<td>8</td>
<td>Coordinate y of the luminaire in anticipation</td>
</tr>
<tr>
<td>9</td>
<td>Anticipation directions</td>
</tr>
<tr>
<td>10</td>
<td>Yes/No anticipation</td>
</tr>
</tbody>
</table>

C. Registration of Occurred Detections

Each luminaire stores the detections made to avoid sending repeated messages and to stabilize communication. When a luminaire receives a message that a detection has occurred, it registers the luminaire it detected and then rejects messages originating from the same luminaire that it detected. The luminaire records in a circular buffer the coordinates of the luminaire it has detected and the instant of time it has received the message. And then the luminaire only accepts a new message from the same luminaire after a period of time.

D. Path Anticipation Algorithm

The prediction of a trajectory is determined by the occurrence of two neighboring detections. In moment a) of Fig. 6 the luminaire L13 detects a presence which then sends a message to its surroundings. The L12, L22, L23, L24 and L14 luminaires record the event of the detection of L13 and illuminate with medium intensity. In b) the pedestrian, when detected by L23, anticipates the trajectory towards L33, L23 sends an anticipation message that the luminaire L33 receives and verifies that it’s in the predicted direction at a range lower than AR=2 and illuminates with intensity high and propagates the message. The L43 luminaire receives this message, and as it’s at an equal distance AR, it’s the last luminaire on the trajectory to light with high intensity and warns its surroundings to light. The luminaires marked with an asterisk (*) light up for a shorter period (2
seconds) and at the end of this period the luminaires return to their previous state, as shown in c) in which the pedestrian stops. Thus, instead of completely turning off, these luminaires return to the previous memorized state. This memory mechanism aims to reduce the impact of incorrect anticipated trajectories in lit luminaires.

For the luminaire to be able to alert the neighborhood to anticipate in multiple directions, the directions information is encoded with a byte (8 bits). Where each bit corresponds to a direction, as illustrated in Fig. 3. For example, the luminaire when anticipating in direction (1,1) that corresponds to bit 0 and in direction (-1,1) that corresponds to bit 2, the luminaire sends a message with directions 00000101.

E. Trajectory Anticipation Filter

The detection boundary problem described in section III-A causes errors in anticipation which results in increased energy consumption. To avoid this problem, a Trajectory Anticipation Filter (TAF) is implemented, which discards invalid anticipations.

In the example of Fig. 7 (reviewed in section III-A) the trajectories in L33 and L34 are intended to be selected and the others eliminated. To this end, the luminaire analyzes the detections occurring in time and space.

In the filter implementation, two conditions are stipulated: Condition 1 - detections occurring in a short period of time (time_min) will be ignored to anticipate trajectories, as for example, in Fig. 7 the trajectories towards L22 and L25 are eliminated; Condition 2 - priority in horizontal and vertical trajectories when two or three presences are detected on the side of the luminaire in a short period of time (time_diff), as for example, in Fig. 7 the trajectories towards L32 and L35 are ignored;

The horizontal and vertical trajectories are selected when there are two or three neighbouring presences on a side and that occurred in the same period of time.

For the problem of diagonal movements at the borders, the implemented filter does not present significant changes in the expected result of Fig. 5, only one of the trajectories towards L52 or L25 is filtered due to the first condition of the filter. The implemented filter benefits from group movements of people, as for example, in Fig. 8 where a group of 3 people move at the same speed and in parallel trajectories. This eliminates all incorrect trajectories.

V. PROTOTYPE TESTING

A. Testing Environment

The presented algorithm will be tested in a network of 12 nodes close between them, as shown in Fig. 9. The Arduino board located in the upper right corner, called gateway, is responsible for simulating detections and sending configurations.
B. Characterization of Spaces

In the simulation in spaces of garages/underground parks and open-space offices, the network of luminaires is implemented in a 4x3 matrix. And in warehouse and corridor spaces, the network is configured in a 6x2 matrix with an obstacle shown in Fig. 10, to ensure that the luminaires do not communicate horizontally.

In the example of an underground car park, only the movement of pedestrians is analysed, disregarding the circulation of vehicles. In any underground car park there are obstacles, such as columns, places for shopping carts and sections that divide the car park, which will not be considered due to the dimension presented.

To simulate the existence of obstacles, a 6x2 matrix is presented with an obstacle that represents the shelves of a warehouse. So, in this example it can be considered that there are two parallel corridors.

C. Types of Movement

In the prototype test, different patterns of people's movements will be simulated, to test the efficiency in predicting trajectories. In which there will be movement of people in groups in the same direction, crossing paths and singular movements. The number of people to detect is limited due to the size of the space to be simulated, because for larger numbers of people it means that the network of luminaires will be all lit up, which makes obtaining data difficult.

D. Tested Movements Patterns

To demonstrate the good performance of the algorithm, the examples described above were tested. The results of the movements and their anticipated trajectories were correctly demonstrated in both matrices.

E. Multiple Movements Testing

In this chapter, the set of the movements show in Fig. 11 is simulated with a duration of 70 seconds and with the network configured in 5 types: 1, 2 - with the default lighting settings and with condition 2 of the TAF filter off and on; 3, 4 - lighting settings HR=0, MR=0, LR=0 and AR=2 and with TAF filter condition 2 off and on; 5 - and finally with the network configured with HR=4, which aims to simulate a car park in which the entire space is lit when movement is detected.

Fig. 11 shows the following 7 circulations to be simulated in numbered order.

![Image](image-url)

In the analysis of the results obtained from the five simulations, the values presented in table II were obtained. Where HR=0, MR=1, LR=2 and AR=2 represents the standard lighting configuration.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>MOVEMENT SET SIMULATION RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR=0 MR=1</td>
<td>TAF Off</td>
</tr>
<tr>
<td>LR=2 AR=2</td>
<td>449.5</td>
</tr>
<tr>
<td>HR=4</td>
<td>0.12</td>
</tr>
<tr>
<td>Total energy consumption [Wh]</td>
<td>557</td>
</tr>
<tr>
<td>Average of received messages</td>
<td>143</td>
</tr>
<tr>
<td>Average of sent messages accepted</td>
<td>71</td>
</tr>
</tbody>
</table>

When analyzing the results of the simulations with condition 2 of the TAF active and deactivated, it’s concluded that they are identical due to the reduced dimension of the network. Because some of the incorrect anticipations that are corrected with TAF filter occur outside the limits of the size of the network, and that the incorrect anticipations have a shorter illumination time.

The network is configured with HR, MR and LR equal to zeros to only illuminate trajectories and detections with high intensity. And in this configuration, energy savings of 43% were obtained compared to the standard configuration and 64% in relation to the configuration in which the space is fully illuminated when detection occurs.

In the simulation with the HR=4 configuration, it presents higher
consumption with an increase of 56% compared to the simulation with the standard configuration with the active filter. With HR=4 the number of transmitted messages increases because all luminaires retransmit received messages.

Compared to a car park in which the entire space is illuminated when it detects movement, the algorithm with the standard configuration (HR=0, MR=1, LR=2 and AR=2) presents an energy saving of 36%.

In the standard configuration, almost all the luminaires are on, which makes it impossible to complete energy saving targets for a reduced size of the network.

VI. CONCLUSION

In this dissertation, an intelligent lighting control solution was developed for large spaces without natural light. Where a decentralized architecture is implemented that offers the functionality to illuminate the users' path in advance. A fully distributed and modular approach was explored, in which each node of the network operates autonomously without the use of a central unit. With distributed processing it’s possible to obtain a scalable solution applicable to larger systems. The decentralized network remains operational if one or more luminaires break down, as the necessary information retransmission can be carried out through the neighboring luminaires.

The developed algorithm presents an energy saving of 36% compared to a car park in which the space is fully illuminated when it detects movement. But it is expected that energy consumption may decrease if network parameters are changed, such as decreasing ranges, lighting times and lighting intensities.

In comparison with the algorithm simulated by Miguel Amado [5], an approach was made to improve trajectory anticipations by applying the TAF filter. Though, with the same parameters (number of luminaires, ranges, times, and intensities) it’s expected that the algorithm presented in this dissertation will achieve better energy efficiency.

However, it was not possible to demonstrate energy saving targets for this prototype in very large spaces, due to the small dimension of the implemented network. Therefore, it’s noticeable that the algorithm presents an excellent performance compared to the results obtained in terms of energy savings.

REFERENCES