Energetic Efficiency in Large Spaces
Illumination

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Abstract— Underground parking spaces consume a large amount of energy in their illumination. If they have a poorly lighting managing system, there can be many situations where areas that don’t need to be lighted, have the light fixtures on. This can lead to energy waste. Nowadays, there are intelligent lighting systems that offer good lighting solutions; nonetheless they can have costly and invasive installations that discourage the business owners to update their system. We propose a decentralized control algorithm that predicts the user’s direction, and lights the path in front of him. To do so, we assume the use of an intelligent fixture that is able to communicate with other fixtures, can make decisions and control the lights intensity according to the situation in hand. Our objective is to create a generic device that is flexible in all situations, and can achieve energy savings, whilst providing a comfortable and secure lighting environment.

I. INTRODUCTION

In order to decrease energy consumption, people are trying to save energy everywhere they can. When it’s the consumer who pays the price, he tends to turn off lights and electric equipment in order to pay a smaller electrical bill, whereas when it’s a case of the illumination of public spaces, the user distances himself from the responsibility of turning off the lights, because he doesn’t pay the energy costs. When it comes to energy consumption in public buildings, the illumination can be the second most energy consuming area. In the Office segment the AVAC system represents 40% of the total energy consumption, and the lighting represents 35% [1]. An intelligent lighting system can create savings of 30% to 50 % [2].

Most of the lighting control systems use a central processing unit. They use sensors to capture the information about the space that is being controlled, and transmit commands to actuators in order to control the lights. There are different types of sensors:

- **PIR sensors** (Passive Infrared Sensor) detect a moving person or if a space is occupied. They are widely used in home automation systems.
- **Light sensors** are used to measure the illuminance levels. They can be used to dim the lights when there’s enough illumination from the daylight. This process is called daylight harvesting [3].
- **CO₂ detectors** are used in underground parking to control the air quality. They also can be used to ascertain the presence of people in a room. However, they are to slow to react to a change of scenario being impractical in lighting control.
- **Cameras** can be used to sense occupancy and control the lighting accordingly to that information. They can be expensive and bring up privacy issues. [4]

Ref [4] proposes a soft sensing technique that uses opportunistic context sources. These sources are mobile phones, Wi-Fi access points, electronic access cards, or others that contain information where their user might be.

There are different types of illumination control that can be used to control the illumination of an underground parking area.

There’s occupancy-based control, which consists in turning the lights in a room or space where a presence is detected. Some systems establish a timer to countdown when they’ll turn off the lights and others start a dimming process also to turn the lights off when there’s no longer anyone detected [5].

Scheduling-based control can be used in business’s or office’s garages where there are opening and closing hours. Normally it’s used together with others types of control in order to produce better savings [6].

To dim the lights to the right level, some systems use light sensors to determine the illuminance and provide the right intensity [7].

Reviewing relevant publications in the field, two case-studies of above ground garages were found where is used a lighting system, that predicts the direction that a person is going to take, and increases the light level in that anticipated area [8] [9]. This system is called ADURA, it’s centralized, lights the path in front of the occupants and uses daylight harvesting on the perimeter of the structure. In one of the studies [9] it’s done a retrofit of the illumination and installed LED lamps capable of working in three different dimming levels: 100%, 60% and 30 %. It’s said that the retrofit cut lighting energy use by 67%. From this savings, 9.5% is obtained solely by the control algorithm.

This mark is going to be used has an objective to achieve or surpass by the algorithm that it’s going to be created.

II. LIGHT QUALITY IN UNDERGROUND PARKING SPACES

The light quality in underground parking spaces must abide by illumination standards. The follow light characteristics evaluate that quality:

1) Luminous Flux (Φ)
Quantifies the radiation emitted from a light source (with a wavelength between 380 nm to 780 nm) in lumens.

2) Illuminance (E)
Is the total Luminous Flux incident on a surface area. Measured in lux, it has defined levels for the type of activity being done in illuminated public space. For example, a public workspace that requires reading or writing activities, the illuminance should be 500 lx.

3) Color rendering index (CRI)
Represents the capacity of a light source reproducing the color of the object where it is reflected in a percentage.

4) Color temperature (K)
It’s the color appearance of the radiation emitted by the light source. With higher temperature, the emitted light is brighter. A good white-yellowish color has a color temperature of 3000 K.

The European standards for lighting installation of parking structures demand a minimal illuminance level of 150 lux with a CRI of at least 60%.

The algorithm is going to consider a LED lamp fixture of 47 W capable of producing 3710 lm with a white light (4000 K of color temperature). We are going to assume that these lamps can provide 500 lx to an area of 7.5 m$^2$.

III. DISTRIBUTED SOLUTION

The proposed lighting control system consist on an installation of several smart light fixtures that communicate with each other in order to decide if they have to turn on the lights. Each one of the luminaires has a PIR sensor and it’s able to detect if a person is passing bellow them. When one detects a person, it starts a chain of messages informing the surrounding fixtures and sending instructions to turn on the neighbor lamps with a medium dimming level. This way, the person will be able to see his surroundings. The luminaires that received the messages will also be able to send new ones expanding the area that is lighted upon detection.

The detecting light fixture will process an anticipation algorithm trying to predict the direction of the person. This information will be included in the messages to instruct the luminaires that are located on the anticipated position to turn the light on with a high intensity level.

IV. LUMINAIRE AND COMMUNICATION

A. The intelligent Luminaires

The luminaires will run like a state machine. They’ll have five possible states:

Detected State – When a luminaire detects a person, it enters this state. It sets the lamp to a high intensity level, runs the anticipation algorithm and broadcast messages.

Anticipation State – A luminaire is set to this state when a person is coming in its direction. It switches the light to a high intensity and sends messages to its neighbors telling them to establish a surrounding environment with medium intensity lighting. It can propagate the anticipation directions to other light fixtures in order to accomplish a greater length of anticipation.

Neighbor Medium State – This is the state in which the surrounding fixtures to a detector fixture are set. It sets the light intensity to a medium level and sends messages to other luminaires to convey instructions from the detector fixture or from the anticipated fixture to further luminaires.

Neighbor Low State – This state makes the visual transition between the lighted area and the dark area. It sets the lamp to a low intensity level. This will be the state of the fixtures localized in the perimeter of illumination. This state doesn’t transmit messages making the communication a converging process.

Idle State – When a light fixture is off waiting for instructions, it’s in this state.

The states are ordered by priority of operation. They all have a duration time that can be configured. A luminaire can always ascend to a state of higher intensity if it’s instructed via message or detection, but can only descend to a lower intensity state if the current state timer expires. When a state of high intensity (Detected or Anticipated) expires in a fixture, it transitions to a medium intensity state (Neighbor Medium). When a medium intensity state expires, it transitions to a low intensity state (Neighbor Low State). Finally, when a low intensity state expires, it transitions to the Idle State where the lamp is turned off. This way, there’s a gradual dimming of the lights instead of suddenly turning off the lights.

![Figure 1 – State machine model of a luminaire](image)

B. Communication

It was decided that the communication was going to be limited to the neighbors. This way it can be faster and more localized. Each luminaire has a unique identification and, upon its installation, is configured with the identification of its direct neighbors. This will be one of the few initial configurations to install the fixtures.

To prevent the communication from spreading indefinitely, two variables of control were created: the Lighting Radius (LR) and the Anticipation Radius (AR).
The Lighting Radius defines the length in number of lights of the surrounding area with a medium intensity level. In the communication process, the detector sends a message to the neighbors with a Lighting Radius value. The first level neighbors decrement that value and send a message to their neighbors and so forth. When a fixture receives a message with a LR of zero, it stops the communication and activates the Neighbor Low State (the perimeter state).

The Anticipation Radius works in a similar fashion but for the anticipation length. The detector runs the anticipation algorithm and includes in the sent messages the anticipation directions and an AR value. When a receiving neighbor is on an anticipated position, it decrements the AR value and sends new messages with the anticipation direction that it is on. In this case, the new messages have a new LR value so that the anticipated fixture can have the same surrounding illumination that a detecting fixture has. When a luminaire receives a message in an anticipated position with an AR value of zero, it stops sending anticipated directions and sends only the LR equal to the used in the detection messages. This way, the anticipation communication also converges.

The light fixtures will have a filtering procedure that rejects messages that don’t bring new information. Because every luminaire is their neighbor’s neighbor, they are bound to receive messages regarding their own detection. Nonetheless, those received messages have no new information about the state, but can have other important information. So there is going to be a redundancy in some received and processed messages. This redundancy can also be an advantage since it ensures that, even if some messages are lost in the communication, the other will convey the information that could’ve been lost.

The filter and the state priorities ensure that the system can function with a convergent communication without loss of information.

C. The Messages

The messages containing new information are stored on a list. This way, when the luminaire receives a new message, compares it with the stored ones to apply the filtering process.

The messages contain the following information:

- Detector – This is the identification of the luminaire that started a chain of messages. With this information, the receiving luminaire can search the stored messages to ascertain if there’s new information regarding this detection. The receiving luminaire also uses this information to register the detection if it happened in one of the neighbors using it in the anticipation algorithm that is going to be described in the next chapter.

- Sender – This is the identification of the luminaire that sent the message. It further helps the filtering process. The receiving fixture can also use this identification to confirm if the sending luminaire is a neighbor.

- Anticipated directions – These directions are vectors to where the user is expected to go. They point to other luminaires and when summed to the Anticipation Sender give an anticipated fixture’s identification.

Anticipated Sender – This is the identification of the luminaire that sent the anticipation directions. They could’ve been obtained by resending anticipation information from another fixture or from running the anticipation algorithm. This identification also makes the anticipation directions unique in their propagation.

Time Stamp – Each message contains the time interval from when it was sent. This helps the filter to distinguish the messages from a present situation of a past situation.

The message size was calculated assuming the following variable’s dimensions:

<table>
<thead>
<tr>
<th>Information</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Stamp</td>
<td>4 Bytes</td>
</tr>
<tr>
<td>Luminaire ID’s (three)</td>
<td>12 Bytes</td>
</tr>
<tr>
<td>LR e AR</td>
<td>2 Bytes</td>
</tr>
<tr>
<td>Anticipation Directions</td>
<td>1 Byte</td>
</tr>
<tr>
<td>Total</td>
<td>19 Byte</td>
</tr>
<tr>
<td>Total + overhead</td>
<td>25 Bytes</td>
</tr>
</tbody>
</table>

Table 1 – Message size

Considering the Zigbee technology, which has a typical rhythm of 250 kbits/s, it would be possible to send or receive 1280 messages per second. This value is considered more than enough for a good functioning of the algorithm.

V. ANTICIPATION ALGORITHM

The anticipation algorithm will use the neighbor detection information to anticipate paths. The algorithm is going to assume that a person is always going in the opposite direction from which he come from.

When a luminaire receives a message with information of detection in a direct neighbor, it’s going to store that information during the same amount of time of the configured state duration. When it detects a person, it’s going to analyze the surrounding past detections to anticipate the contrary directions. For example, if the light fixture that detects a person consults its neighbor detections table and verifies that the neighbor fixtures in the northwest and in the west directions have detected a person in a recent past, it’s going to anticipate the neighbor fixtures to the east and south east (consult figure 2).

With this method, the luminaire is capable of anticipating in all directions at the same time (if different persons are coming from opposite directions).
VI. SIMULATIONS AND TEST

To test the algorithm, a simulation platform was developed in Java programming language. The simulation implements a matrix of luminaries that run the algorithm previously described. Their identifications are the matrix index numbers.

In a real life application, the area that the PIR sensors can detect is usually a circle, but for simplification purposes, the program considers the area of detection of each luminaire a square.

To simulate the algorithm, the program loads a text file that has a preset number of people with preset paths. Then the program will run a series of iterations. In every iteration, a movement vector is going to be added to each person location. Then the program will run the algorithm for each detected person in their new position, one at a time. In the simulation the program is entirely sequential, diverging from real life. But, because of the time stamps on the messages, the information is treated like it is happening at the same time. Each luminaire only knows the neighbor information from the initial configuration and the information that receives from messages, so the system runs a fully decentralized architecture.

A. Configuration

The testing platform the following features of configuration:

Adjustable Lighting Radius – LR can be adjusted to a preferred value. If it’s chosen a high enough value, the algorithm could turn all the lights of the study area in a medium light intensity. This shows the flexibility of configuration in this algorithm.

Adjustable Anticipation Radius – AR also can be adjusted to a preferred value. If it’s zero, there’s no anticipation.

State duration times – The duration of the state can be adjusted. This helps the system to adjust better to the time that a person takes to cross a light area of detection. If the state is too long, the lights will stay an unnecessary time turned on. If it’s too short, the system will turn the lights off faster, creating an unappealing dark space behind the walking person.

Power down duration times – These are the duration times of the Neighbor Medium and the Neighbor Low states when they are initialized because a higher intensity state expired. By regulating these times, the power down effect of the lights can be changed.

Types of lamps used – Most ran simulations used the 47 W LED. But the program has the capability of changing the lamps to adapt to different densities of light fixtures deployment. It can simulate a higher fixtures density scenario, using less consuming (and therefore with lower areas of illumination) or a scenario with a disperse deployment of fixture using higher power lamps (and therefore with higher areas of illumination).

Dimming levels – The dimming levels for the high, medium and low intensity can be set to a desired percentage.

All light up – The platform can be set to turn all luminaires on with a high intensity level as soon as a person is detected. This feature is used to mimic a more traditional algorithm so it can be compared to the developed solution.

With these configurations options it’s possible to test various types of control.

B. Features

The program is able to make calculations of the energy consumed during the simulation. The total energy is given by:

$$W = \left( \sum_{i \in \text{Cat}} P_{\text{Cat},i} \log d_i \right) \times 3600$$

(1)

The energy consumed in each simulation is very low, because the simulations duration time is also very low (the longest simulation represents no more than three minutes of operation). However, the objective of the test platform is to obtain comparative results and not absolute value.

The luminaires are going to have the capacity to establish a minimum state of operation. With this feature, they are capable of maintaining a preset intensity level even when there’s no stimulation happening (detection or communication). Luminaires with this option set in a high intensity can be installed in the garage entries/exits to show...
the user always where they are located. Setting it in a low intensity, luminaires can be installed near the walls, in order to further strengthen people’s sense of security.

After some testing, a new feature was computed in order to make the algorithm more attractive. When a person enters the simulation space, or stays motionless, below a functioning light fixture, the detecting luminaire is going to anticipate all directions if it hasn’t any previous neighbor detections. This way, when a person enters the space or stops to make a decision, it will have an inviting environment and better lighting to choose a path.

The program was created in a modular structure. This means that it has interchangeable classes that can be substituted with another in order to try different algorithms. The anticipation part can easily be substituted, maintaining the communication part. This feature was set to permit an easier update or change in the algorithm.

C. Tests and lighting effects

Various simulations were conducted to verify the influence of the variables.

The anticipation algorithm works well for straight paths. If a person makes a turn of ninety degrees it won’t be able to anticipate this turn. Nonetheless, the surrounding lighting maintains the unpredicted position illuminated and the system is quick to anticipate a new path as soon as the person steps in the unpredicted luminaire detection area.

When a person is walking along the frontiers of detection of two light fixtures, the anticipation algorithm produces over-lighting. This happens because there are two lights anticipating opposite ways.

When a person walks diagonally, the algorithm anticipates three directions, as if it is trying to guess if the person is going to turn to a horizontal path or a vertical path. With a large value of AR (four is considered a high value for AR), it also can lead to over-lighting.

When two people intersect, the anticipation algorithm is also going to over-light the space. This happens because the position from one user influences the anticipation of the other use when they are in neighbor positions to each other.

To study the number of messages in a simulation, a worst case scenario was created. In it, thirty five neighbor fixtures detect movement at the same time. Because they are all neighbors, the anticipation algorithm is going to anticipate all directions, creating a dense communication. The results are represented in table 1:

<table>
<thead>
<tr>
<th>Thirty Five Adjacent Detecting Luminaires Simulation</th>
<th>Total number of messages on an iteration</th>
<th>Maximum number of messages received in one luminaire</th>
<th>Number of processed messages in that luminaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR=1 and LR has different values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LR = 0</td>
<td>1880</td>
<td>57</td>
<td>25</td>
</tr>
<tr>
<td>LR = 1</td>
<td>1880</td>
<td>57</td>
<td>25</td>
</tr>
<tr>
<td>LR = 2</td>
<td>7544</td>
<td>170</td>
<td>26</td>
</tr>
<tr>
<td>LR = 3</td>
<td>37219</td>
<td>845</td>
<td>123</td>
</tr>
<tr>
<td>LR = 4</td>
<td>110576</td>
<td>2168</td>
<td>191</td>
</tr>
<tr>
<td>AR=2 and AR has different values</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AR= 0</td>
<td>2488</td>
<td>72</td>
<td>9</td>
</tr>
<tr>
<td>AR= 1</td>
<td>7544</td>
<td>170</td>
<td>26</td>
</tr>
<tr>
<td>AR= 2</td>
<td>13041</td>
<td>219</td>
<td>30</td>
</tr>
<tr>
<td>AR= 3</td>
<td>18689</td>
<td>245</td>
<td>30</td>
</tr>
<tr>
<td>AR= 4</td>
<td>23462</td>
<td>247</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 2 - Number of message in a worst case scenario (situation with a dense communication)

It’s possible to see that, even in the worst case scenario, if it’s used a LR lower then 4 (LR bigger than two is an unlikely configuration to use), the maximum number of messages received by one luminaire it’s lower than the transmission rhythm calculated in the chapter IV. These results show a good message filtering and a feasible communication.

For the variation of AR, when it starts to get higher, the biggest number of messages that a luminaire receives starts to stabilize because the communication is being propagated directionally. This reinforces the directional nature of the AR variable. The same doesn’t happen with the LR because it has a radial nature. It creates a dense propagation.

D. Energy consumption and savings

Some simulations were run, to compare the energy consumed when using different values for LR and AR in different types of paths (straight routes, diagonal routes, and routes along the frontiers of detection of two or more luminaires). It was concluded that a route along the frontiers of detection of two or more luminaires is the most consuming
type of path. In a real situation, to reduce the possibility of people taking this type of path, the luminaires can be aligned with the middle of the crosswalks, so that the person walks in the middle of the detection areas.

Figure 6 – Directions of route along the frontier of detection of two or more luminaires

It was also concluded that if a higher intensity illumination is needed, it’s better to use a higher AR than a higher LR, because it will produce a more intense directional lighting that consumes less energy than the energy consumed in a configuration with a higher LR (LR=3 and LR=4).

The developed algorithm was compared with a more traditional control system that turns all the lights on, as soon as someone is detected. Several simulations were run and the values of energy consumed using the traditional control method were use as benchmark to calculate the possible savings that the developed algorithm can have. This traditional control was simulated with two different high intensities: 80% and 70%.

To compare the possible savings with different occupancy densities of the space, three simulations where compared together: when a person is walking from left to right and vice-versa, when a flow of people is doing the same path as the first simulation, and when different flows of people are doing the same type of route in two parallel paths. The three simulations last the same interval of time, so that the energy consumption using the traditional control is always the same (60.24 Wh for a high intensity level of 80% and 52.72 Wh for a high intensity level of 70%). This way the first simulation had a low occupancy of the space, the second had a medium occupancy and the third has a high occupancy. The savings obtained are showed on the table 3.

Table 3 – Savings obtain for three simulations with three different occupancies rates

<table>
<thead>
<tr>
<th>Simulation of three different occupancies rate of the space</th>
<th>Consumed energy using the Algorithm (Wh)</th>
<th>Savings obtained when comparing with the traditional control with 80% intensity</th>
<th>Savings obtained when comparing with the traditional control with 70% intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low occupancy</td>
<td>15.46</td>
<td>74.3%</td>
<td>70.7%</td>
</tr>
<tr>
<td>Medium occupancy</td>
<td>22</td>
<td>63.5%</td>
<td>58.3%</td>
</tr>
<tr>
<td>High occupancy</td>
<td>33.27</td>
<td>44.8%</td>
<td>36.9%</td>
</tr>
</tbody>
</table>

It’s possible to see that a wide garage that is used by only a few people at a time will benefit immensely from the use of this algorithm when compared with a traditional lighting system, and that even with a bigger number of people using it, the developed system can achieve savings of 44.8%.

In order to truly test the algorithm a simulation that tries to emulate the real world as good as possible was created. It was considered a study space that has entrances and exits, with columns and a path that the user will preferably use (simulation of the crosswalks that a normal underground garage has).

Figure 7 – Representation of the topology space in the simulation platform (a) and a model of the real space on which is based (b)

In this simulation, there will be times with many people using the space, and times that only one user is using it. Most of the paths that the simulated people use are horizontal and vertical in order to simulate the tendency that a person has in using the crosswalks. Nonetheless, irregular paths with diagonal directions and stops are also included in the simulation.

With all these events, it’s possible to study the algorithm behavior to all situations in one simulation and compare the results with a traditional control method.

The results are shown in the next table:

Simulation of a “real environment”

<table>
<thead>
<tr>
<th>LR=2 with different AR values</th>
<th>Consumed energy (Wh)</th>
<th>Savings obtained when comparing with the traditional control with 80% intensity</th>
<th>Savings obtained when comparing with the traditional control with 70% intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>52.16</td>
<td>60.7%</td>
<td>54.9%</td>
</tr>
<tr>
<td>1</td>
<td>61.02</td>
<td>54.0%</td>
<td>47.3%</td>
</tr>
<tr>
<td>2</td>
<td>67.63</td>
<td>49.0%</td>
<td>41.5%</td>
</tr>
<tr>
<td>3</td>
<td>71.8</td>
<td>45.9%</td>
<td>37.9%</td>
</tr>
<tr>
<td>4</td>
<td>74.05</td>
<td>44.2%</td>
<td>36.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AR=1 with different LR values</th>
<th>Consumed energy (Wh)</th>
<th>Savings obtained when comparing with the traditional control with 80% intensity</th>
<th>Savings obtained when comparing with the traditional control with 70% intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>42.97</td>
<td>67.6%</td>
<td>62.9%</td>
</tr>
<tr>
<td>1</td>
<td>47.39</td>
<td>64.3%</td>
<td>59.0%</td>
</tr>
<tr>
<td>2</td>
<td>61.02</td>
<td>54.0%</td>
<td>47.3%</td>
</tr>
<tr>
<td>3</td>
<td>72.6</td>
<td>45.3%</td>
<td>37.3%</td>
</tr>
<tr>
<td>4</td>
<td>79.84</td>
<td>39.8%</td>
<td>31.0%</td>
</tr>
</tbody>
</table>
Table 4 – Simulation of different configurations of the developed algorithm using emulating a real environment

Using what is believed to be a good lighting environment (LR=2 AR=1), it’s possible to obtain a 54% reduction in energy consumption when comparing the new algorithm with a traditional control method.

These results show that the algorithm can bring great savings to an illumination system, and it’s assumed that its cost of implementation can be quickly amortized.

VII. CONCLUSION

After testing, it was possible to determine that this control algorithm can save a high amount of energy. Comparing with the benchmark [9] it can surpass the mark of 10% savings in all configurations. It can achieve 54% in a simulation with paths that aren’t beneficial for the algorithm. With simpler and constant paths with less people using it, up to 74% of savings were achieved. It’s believed that with a LR of two, and an AR also of two, it’s possible to attain a comfortable lighting of the space, while saving energy consumption.

The flexibility of the created algorithm allows further development by simply substituting parts of it. The modular architecture, on which it was built on, is a strong feature in this development, making it a good model for future studies of the anticipation algorithm. Its communication can be enhanced including more information in the messages so that the luminaires can make better anticipation decisions. The handling of the frontiers of detection paths can be improved so that the system doesn’t produce over-lighting.

In conclusion, the algorithm created can offer considerable savings, and the system is very flexible and easily expandable. It’s believed that the cost of implementation can be easily amortized, making it a very attractive solution.

REFERENCES


