Distributed Control of Illumination in Office-Like Spaces

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***Abstract*—Office spaces, and lighting within them, are one of the major energy consuming sectors and therefore it is very important to develop new ways to improve their energy efficiency. Smart illumination is an interesting solution not only to reduce an office's energy costs but also to increase workers' comfort and performance. By controlling the individual illuminance of each work area, as well as other lighting properties, it is possible to reach optimum working conditions while, at the same time, saving energy. This work aims to develop an optimum control for networked luminaires so that when one light is adjusted, the remaining lights regulate immediately in order to maximize the goals. Different algorithms are used and tested, namely centralized and distributed solutions, in order to assess which is the most efficient while at the same time providing the best possible user comfort. While doing so, several tools had to be developed: a dedicated communications system (LampCom protocol) for better performance of the algorithms by providing the most efficient communications between luminaires; a simulation environment to test the algorithms that were developed and to have easy access to results; a dedicated test-bench to evaluate the algorithms' performance in the real world and innovative metrics to evaluate the algorithms' comfort performance.**

A distributed algorithm with prediction and error compensation, also called distributed with automatic learning, was developed and achieved energy savings of approximately $60\,\%$ on the scenarios where it was tested, while maintaining an adequate user comfort. This results are also superior when compared to other systems that already exist.

***Index Terms*—Office spaces, distributed control, energy savings, productivity.**

I. Introduction

Buildings account for 30% of all energy consumption globally and a significant share of greenhouse gas emissions. Amongst the systems that consume the most energy are lighting systems [1]. New buildings that are deliberately built with energy efficiency in mind can reduce energy consumption up to 50%. Clearly, efficient buildings are cost-effective and therefore can save consumers a significant amount of money on their energy bill [2].

Several characteristics of lighting such as illuminance (the intensity of light that impinges on a surface), amount of glare and the spectrum of light are known to affect workers performance. The human system repeats itself approximately every 24 hours, which is called a circadian rhythm and it has been proven that lighting characteristics such as brightness, intensity and color can change this cycle, thereby also affecting their comfort and performance [3].

Using a sensor to evaluate the presence of a person at an office desk and using an intelligent control, it is possible to not only save energy and consequently reduce the running costs of a company, but it is also possible to have workers be more productive [4], [3].

In an office-like space there are many factors that contribute to the brightness and color temperature of the light on each specific space. Controlling the brightness and color of the light at a working desk represents a challenge because merely regulating the power of the light above the desk is not enough. Every light surrounding that desk, as well as exterior light, have a contribution. Moreover, color of surrounding objects, distance between the luminaire and the desk and the objects placed around it all influence the light that reaches the desk's user. The biggest challenge in such a scenario is to smoothly dim the luminaires to the optimum state because of the fact that each luminaire influences each other.

Three possible types of control for a smart lighting system are:

- Individual control.
- Centralized control.
- Distributed control.

It is proposed that a distributed control is the best alternative to command the luminaires and research is done to determine which algorithm is the best to optimize the problem. Regardless of the method chosen, the goal is to devise an optimization problem in order to study which algorithms can solve it, under which conditions do they converge and what are the convergence rates, which translate into better comfort for the users and lower energy consumption.

In particular, the contributions of this work will be:

- Development of more efficient distributed algorithms applied to the control of illumination systems, allowing for faster convergence rates and therefore saving more energy.
- Development of an algorithm with smoother transitions which allow for minimal, or no oscillation at all, of the state of the system, meaning that it will converge immediately to the optimum solution. This will provide better user comfort.
- Algorithms which can carry out daylight harvesting and therefore reduce the total energy consumption of the system.

- Comparison of performance between different types of control and different implementations.

II. Concepts

Automatic illumination is usually achieved using a presence and a luminance sensor and a microcontroller to process the data from the sensor and actuate according to the algorithm used. Since LED luminaires are being used, actuation is done through Pulse Width Modulation (PWM), which enables to control the amount of light emitted. Depending on the luminaire, other controls might also be available, such as light color.

A. Luminaires

Luminaires, also known as light fixtures, are perceived as a complete lighting unit, constituted by the light and the parts that distribute the light, position the lamps and connect them to the power supply. To choose a luminaire that can efficiently provide appropriate illuminance, to the application it is being used for, is an important part of energy efficient lighting design [5]. In this work luminaires are considered as a complete lighting unit with the following components:

- A LED light source.
- A ocupancy sensor and a brightness sensor.
- A communication module.
- A microcontroller.

B. Daylight harvesting

This technique consists of compensating for natural daylight coming into the room [6]. Because on rooms with windows the amount of sunlight depends on the season and time of day, and taking into account that the objective is to have a constant light incidence at each work area, then the amount of light emitted from each luminaire should compensate for the daylight received. To accomplish this, the luminaire's sensors evaluate the amount of daylight and dim the luminaire accordingly. This can allow for greater energy efficiency while also providing users with better visual comfort [7].

C. Scheduling

The amount of light throughout a normal day is not constant and the human body subconsciously acknowledges these slight differences. Workers on a closed room with little or no daylight can have decreased performance due to the lack of stimulus from daylight. One way to compensate for this is to vary the light properties of the luminaires along the day, following the patterns of normal daylight thus creating a sensation of being outdoors [3].

D. Illumination requirements for different tasks

Illumination in an office-like space depends on several factors, namely on the task that is being performed and on the number of people present and their age. A usual value that is considered appropriate for office illuminance is 750 lux [8]. The color of the luminaire is also very important, as is the color of the background and this means that the focus direction of the luminaire should be taken into account [9], [10], [11].

TABLE I: Comparison of illuminance levels required for the most common office tasks.

Task	Illuminance level (lx)
Filing, copying, etc.	300
Writing, typing, reading, data processing	500
Technical drawing	750
Conference and meeting rooms	500
Reception desk	300
Archives	200

According to the European standard EN 12464-1 "Lighting of indoor workplaces" from April 2013, different office tasks require different illuminance levels that are represented in Table I.

III. Related Work

Different approaches to control have been used, of which the most important are centralized control and distributed control. Independent control would be the easiest to implement because there is no need for communication between devices however, it would also be the one to struggle the most to achieve a solution because there is no exchange of information between devices and the decision process is not an informed one. Apart from that, distributed control would be the easiest to implement because a large centralized system would not be needed, however it is harder to achieve an optimum solution and it is not as robust when compared to a centralized control system [12]. One of the objectives of this work is to improve distributed control in smart illumination applications because it would make such a system easier to implement and use less processing resources.

A. Literature

The subject of smart illumination has been addressed by different authors, and different approaches have been used, whether distributed control or centralized control and with different purposes. The most relevant are the centralized systems developed by two companies, Zumbotel[1] and Encelium[2], and one system from academia, which is one of the few systems available of distributed control of illumination, which states it can achieve an average power saving of 50 % [13].

As Table II shows, a distributed control system is seldom used on a smart illumination environment. This might be because it is a harder type of control to be implemented, however it might result on a easier hardware implementation since there is no need to guarantee a robust communication to a central processing unit. The greatest advantage of a distributed control system is that each light fixture will have its own informed decision making process because each fixture will be communicating with neighbor devices, therefore taking into account their influences. Furthermore, there is no commercial

[1]http://www.zumtobel.com/
[2]www.encelium.com

TABLE II: Comparison between different commercial systems (Zumbotel and Encelium), our system and a scholar system that is being developed called DCI standing for Distributed Control of Illumination. ● represents an included feature and ○ a non-included feature.

Features	Zumbotel	Encelium	DCI	Our system
Presence detection	●	●	●	●
Scheduling	●	●	○	○
Daylight harvesting	●	●	●	●
Neighbor lights' influence	○	○	●	●
Color temperature adjust	●	○	○	○
User personalization	○	●	○	○
Light threshold limits	○	●	○	○
Centralized control	●	●	○	○
Distributed control	○	○	●	●

system that accomplishes a steady illumination factor over a specific working area. That means that a luminaire might be dimmed according to the presence of a person on a working area but it does not take into account the influence of neighbor luminaires.

IV. Solution

The proposed solution for a distributed control type of illumination in an office-like space is to have a luminaire above each working area, comprising a presence detector and a light sensor and having a processing unit that decides locally the dimming level of that specific luminaire. The decision process however is an informed one because there is a communication established between each luminaire and all the other surrounding luminaires therefore making decisions knowing the state of the other luminaires. The influence that each luminaire has on others must be evaluated so that the system knows the influence that changing the dimming level on one luminaire will have on the others before actually performing the action.

Building a distributed lighting system is based around an optimization problem, which can be described according to Equation 1, which is subject to Equation 2, where $E_{m,i}$ is the element from line m and column i of the coupling matrix E, $\mathbf{d}$ is the dimming vector, O_m is the external light influence on luminaire m, t_m is the illuminance lower bound for the given task and occupancy state, which is also the target for illuminance, of luminaire m and N_m represents the connectivity between luminaires to luminaire m.

$$\mathbf{d} = arg\min_{d} \sum_{i=1}^{N} d_i \tag{1}$$

$$s.t. \begin{cases} \sum_{i=1}^{N} d_i E_{m,i} + O_m \geq t_m, m = 1, ..., N \\ 0 \leq d_m \leq 1, m = 1, ..., N \\ m \rightarrow N_m, m = 1, ..., N \end{cases} \tag{2}$$

These equations mean that it is intended to bring the energy consumption down to a minimum while maintaining a comfortable illuminance level to the tasks that are being developed. According to this model, which uses a coupling matrix and takes into account the external light influence, this variables have to be computed through a calibration process or have to be estimated, since they depend on factors that are external to each luminaire.

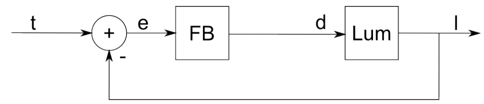


Fig. 1: Block diagram of a reactive type of control where t is the target illuminance, e is the error, d is the dimming value, l is the actual illuminance, FB is the feedback controller and Lum is the luminaire block.

Fig. 2: Block diagram of a predictive type of control, where t is the target illuminance, d is the dimming value, l is the actual illuminance, FF is the feedforward controller and Lum is the luminaire block.

The approach to solving this problem can be done in many different ways, of which the ones that will be approached are using a local control, a centralized control and distributed control. While the former type of control is reactive, that is, adjusts the illuminance level based on the readings that each luminaire's sensor is giving, the two latter types (centralized and distributed) are of the predictive type. This means that they actively attempt to predict what the illuminance level is going to be based on the information each luminaire has in its possession.

A reactive type of control is one of the easiest to implement using a Proportional-Integral-Derivative (PID) controller and its block diagram is in Figure 1 where t is the target illuminance, e is the error, d is the dimming value and l is the actual illuminance.

While a simply reactive control may be simple to implement, its reaction time may be somewhat lengthy. A predictive type of control can reach faster convergence times because it can instantly change the dimming value to have the desired illuminance. The block diagram of this type of control is represented in Figure 2, where t is the target illuminance, d is the dimming value and l is the actual illuminance.

Although the predictive type of control may have faster convergence times, it may not always reach the correct solution and therefore it becomes necessary to complement it with a reactive controller. Consequently, the centralized and distributed controls are complemented by a reactive PID controller. The block diagram of such a control is in Figure 3, where t is the target illuminance, e is the error, d is the dimming value, l is the actual illuminance, FB is the feedback controller, FF is the feedforward controller and Lum is the luminaire block.

A. Simulator

In order to make the control algorithms' development simpler, a simulated environment was created which replicates light physics and which allows to easily test the algorithms'

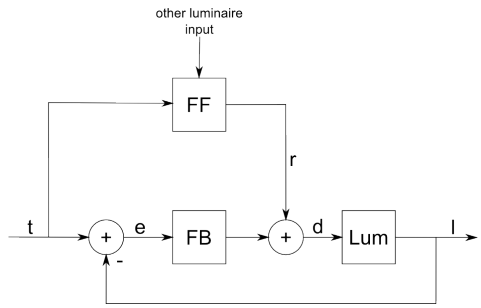


Fig. 3: Block diagram of a predictive type of control with a reactive component, where t is the target illuminance, e is the error, d is the dimming value, l is the actual illuminance, r is the predicted illuminance, FB is the feedback controller, FF is the feedforward controller and Lum is the luminaire block. The feedforward controller may also receive information from other luminaires.

performance. A widely used model for the illumination pattern of an LED is the Lambertian function, which can be described by Equations 3 to 5 [14].

To compute the lambertian mode, which is a property that defines the reflectance of a surface, Equation 3 was used, where L is the lambertian mode and $\Phi_{\frac{1}{2}}$ is the semiangle of the light beam at half power, which represents the light distribution and is a property defined in the lamp's characteristics.

$$L = \frac{-ln(2)}{ln\left(cos\left(\Phi_{\frac{1}{2}}\right)\right)} \tag{3}$$

To compute the illuminance directly below each luminaire Equation 4 was used as the model, where A is the maximum illuminance per LED, A_0 is the luminous flux, which is the total amount of light emitted by a light source and is measured in Lumen, and h is the distance between the ceiling and the workspace plan.

$$A = \frac{(L+1)A_0}{2\pi h^2} \tag{4}$$

To compute the illuminance, which is the amount of luminous flux from a light source on a given area and is measured in Lux, at any point in a room given by a single light source Equation 5 represents the model that was used, where $l_{i,xy}$ is the illuminance at the point with the coordinates xy of luminaire i, x and y are the coordinates of the point where the illuminance is being computed and x_0 and y_0 are the coordinates of the light source.

$$l_{i,xy} = A \times \left(1 + \frac{(x-x_0)^2 + (y-y_0)^2}{h^2}\right)^{-\frac{L+3}{2}} \tag{5}$$

B. Calibration

Most of the algorithms developed require that data is exchanged between luminaires with information of the light that reaches each one, coming from each of the other luminaires. Because of that, a full calibration of the complete system is required in order to understand how each luminaire influences all the others, which corresponds to estimating the values $E_{m,i}$ of Equation 2.

This is usually done in the following steps, where the calibration is an automatic process:

1) Fully disable all the luminaires.
2) Turn on one luminaire at a time.
3) Have every luminaire register the read values with the knowledge of what luminaire was turned on. These values are to be registered in a matrix or vector called coupling matrix.
4) Turn off the luminaire that was turned on.
5) Repeat steps 2 through 4 for every luminaire on the system.
6) Turn every luminaire at full power at the same time, so that every luminaire has the same reference of what is the maximum possible illuminance.

In case the illuminance sensors are not yet calibrated to do the correct measurements in lux, this calibration process should be done at full dark or with minimum external light influence possible so that every luminaire has the same reference values. However, if the illuminance sensors are already calibrated, step 1) can be used to estimate the external light influence (O_m from Equation 2) and therefore it is not required to have the room in full dark conditions.

C. Algorithms

Algorithm development is one of the most fundamental parts of this work. The algorithms represent all of the intelligence of the solution that is developed and they can have a big impact on the user comfort and energy used. Following is the mathematical formulation of the two most important algorithms during the development of this work: one is a local PID control and the other is the most robust distributed solution that was achieved.

1) Local PID Control: Local PID controllers are widely used in control systems because they are easy to implement and require little processing power [15], [16]. This type of control is simple to design and can achieve good performance and although its parameters may be difficult to tune, there are several techniques that make the process easier [17].

The PID controller is composed of three different components, the proportional, the integral and the derivative part which are applied to the error, that is the difference between the target and the actual value of the parameter that is being adjusted, which in this case is the illuminance. Together these three components allow for a fast and smooth convergence to the result [18]. The PID algorithm is mathematically simple and therefore requires little computational power. However, due to the way it is built, its output is usually in the form of a speed or actuation, which means it is ideal for motor control, for example. On the case of a luminaire, on the other hand, its actuation is done directly on its final state, the duty cycle of the pwm wave in this case. Nevertheless, with a simple modification of the algorithm, it can be adapted to luminaire control. The block diagram of this control is shown in Figure 4. As it can be seen, there is an integrator component so that the

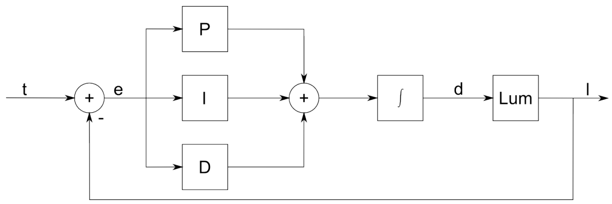


Fig. 4: Block diagram of an adapted PID controller in order to be used in luminaire control, using and integrator after the sum of the proportional, integral and derivative parts. P is the proportional, I is the integral and D is the derivative part of the controller. t is the target illuminance, l is the actual illuminance and e is the error, which is the difference between target and actual illuminance, and d is the dimming of the luminaire Lum.

output of the PID algorithm is the increment in duty cycle of the pwm wave.

2) Distributed with Occupancy, Predictive Coupling Matrix and Error Compensation (Automatic Learning): When it comes to distributed algorithms there are several different factors that come into play. To achieve an advanced prediction system the algorithm must have knowledge of the state of occupancy of all the other luminaires, however it is not necessary to know their illuminance readings. Instead, the illuminance of other workstations is predicted through a predictive coupling matrix. This is because the luminaires can only transmit their current illuminance state and it is more useful to know their future illuminance state, which is best achieved using the predictive coupling matrix.

The way this predictive coupling matrix is computed is at the calibration stage where, instead of having each luminaire at maximum power in turn and reading the values in each one of the other luminaires, there is a PID local controller that will power each luminaire in turn in a way that it will be providing the target illuminance for when it is occupied r_{500}, set at $500\,\mathrm{lx}$ and then for when it is unoccupied r_{200}, set at $200\,\mathrm{lx}$, providing in fact two reference matrices instead of one, which are predictive coupling matrix e_{500} and e_{200} respectively.

The prediction of illuminance is done through Equation 6, where r_i is the predicted value of illuminance, s_j is the occupancy state of luminaire j and $\overline{s}_j$ is its negation, k is a user defined gain, d_i is the dimming level of luminaire i and O_i is the external light influence, which is the light coming from every other source other than those belonging to the system and can be obtained using the calibration method described in section IV-B.

$$r_i = \sum_{j \neq i}^{N} e_{j200}\overline{s}_j + \sum_{j \neq i}^{N} e_{j500}s_j + kd_i + O_i + \epsilon_i \tag{6}$$

In order to compensate for external disturbances, a new component is added to the illuminance estimation which is able to compensate only when those situations arise. Therefore, an error compensation feature ϵ_i is added. This variable is capable of compensating not only certain limitations present in other algorithms but it also provides a mean to have an adaptive algorithm to new circumstances such as changing external light influence or even changing the position of the workstations or other luminaires, although in that last situation it would be advisable to do a new calibration of the system.

This variable compares the predicted illuminance value from the algorithm with the final value that is actually obtained according to Equation 7 where l_i is the illuminance value at luminaire i, r_i is the predicted value in Equation 6, k is a user-defined gain and t is the time when the values were obtained.

$$\epsilon_i^{t+1} = \epsilon_i^t + k(l_i^t - r_i^t) \tag{7}$$

The assumption is that all individual controllers are able to achieve the desired level of illuminance in their workstations: $500\,\mathrm{lx}$ for occupied workstations and $200\,\mathrm{lx}$ for unoccupied ones. When this is not the case, the adaptive error compensation variable ϵ_i is adjusted to compensate the prediction error.

This algorithm is therefore a predictive type of control, such as the one in Figure 3, where the predictive part that requires transmission of information is the feed forward block. This control also features a feedback block which relies on a PID control for fine tuning the illuminance at a workstation.

D. Evaluation Metrics

To evaluate the proposed methods, the following metrics are used: the energy consumption index and two comfort indexes, which are the illuminance variation index and the illuminance deviation index. The illuminance variation index measures the flicker, oscillations and sudden changes on the lighting that disturb the user's attention. The illuminance deviation index measures the user's discomfort due to an inadequate illumination level for the task at hand.

Average power is directly related to energy consumption but is independent of the duration of the test, so it is the most adequate measurement for energy consumption. It can be obtained by summing the duty cycle throughout the duration of the test. To achieve the average power per lamp, this result must be multiplied by the lamp's rated power, and divided by the number of lamps and the amount of time the system was used during testing. The energy consumption index is given by Equation 8 where E_T is the energy consumption index and $d_{j,t}$ is the dimming vector of luminaire j at time t. P_R is the rated power of the lamp, T is the time period of the testing and L is the number of lamps that were measured during the test. The energy consumption index, which is the average power, is given in Watt.

$$E_T = \frac{P_R}{T \times L} \times \sum_{j=1}^{N} \sum_{t=0}^{Tmax} d_{j,t} \tag{8}$$

Taking into account that one of the comfort factors is for the illuminance to have small variations, then the illuminance variation index is the sum of the derivatives of each luminaire at each moment in time and is represented by Equation 9 where C_{var} is the comfort index of an algorithm and $l_{j,t}$ is the illuminance read at workstation j at time t. In order to read the index as the variation of illuminance in lux per hour, it is necessary to multiply by a constant, where T is the time duration of the test, L is the number of lamps used on testing and 3600 is for the conversion of seconds into hours.

$$C_{var} = \frac{3600}{T \times L} \times \sum_{j=1}^{N} \sum_{t=0}^{Tmax} |l_{j,t} - l_{j,t-1}| \tag{9}$$

One other comfort factor that must be taken into account is the difference between the desired illuminance and the actual illuminance that there is in each workstation. For that purpose, the illuminance deviation comfort index metric must be used in order to compute such a factor and Equation 10 shows its mathematical representation, where C_{dev} is the difference comfort index, $l_{j,t}$ is the illuminance read at workstation j at time t, $t_{j,t}$ is the target, or desired, illuminance read at workstation j at time t and occ_j is the occupancy state of workstation j. In order for the obtained value to be given in average lux deviation per second it is needed to multiply by a constant, where T is the time duration of the test and L is the number of lamps used on testing. Because it is only an issue when there is under illumination on the occasions that the workstations are occupied, than the index only counts on these occasions ($occ_j = 1$ and $t_{j,t} - l_{j,t} > 0$).

$$C_{dev} = \frac{1}{T \times L} \times \sum_{j=1}^{N} \sum_{t=0}^{Tmax} t_{j,t} - l_{j,t},\ occ_j = 1,\ t_{j,t} - l_{j,t} > 0 \tag{10}$$

Due to the way these three indexes are computed, the lower the value is, the better is the performance of the algorithm.

E. LampCom Protocol

In order to have the luminaires sharing information with each other it was necessary to set up a communication system between them. The most common protocols were rehearsed:

- Asynchronous RS232 (UART) protocol does not need a clock line and has full-duplex capabilities. Furthermore it can easily be adapted to the RS485 protocol for communications over long distances. However, multipoint communications are not directly supported by Universal Asynchronous Receiver Transmitter (UART) ports on most microcontrollers, therefore requiring an additional adapter, thus increasing the cost of the system.
- Synchronous I2C protocol is usually used by microcontrollers to communicate with sensors and memories. The way this protocol works is with a master device driving the clock and sending or requesting information from other devices, the slaves. Although this protocol would allow to use multiple devices sharing the same bus line, these devices would only communicate from one point to another, meaning that it would not be possible to make one device broadcast its state to all the others. Furthermore, the need to have one master device and slaves would be an inconvenient to the distributed control algorithm.
- The DALI communication protocol, although it is dedicated for lighting systems, it was developed for communication between a central processing unit and luminaires, thus making it only suitable for central controls. Since the communication requirements for this system mean it must also work on distributed controls, then the DALI protocol cannot be used.

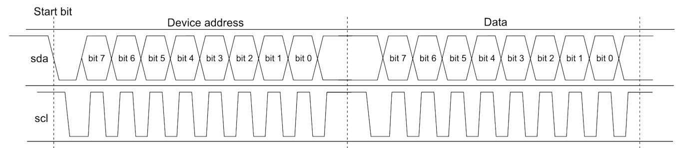


Fig. 5: LampCom timing of the data line (sda) and the clock line (scl). First the origin device address is transmitted followed by the data. The sda line must be stable when the scl line goes to high.

Therefore, a custom communication protocol was created to fit perfectly with the distributed control algorithm's specification. This protocol, LampCom, is inspired in I2C communication in the sense that it uses one clock line and one data line. However, contrary to I2C communication the devices are not divided into master and slaves. Each device has the ability to write to the data line while driving the clock line provided that it is not being used. The I2C protocol is simple, fast, cost effective and well documented, which means it is a good basis for the development of a new protocol.

To assure the bus line is not being used, the lines have pull-up resistors, much like I2C, meaning that when they are not being used they are in a high state. This means that to initiate a broadcast, a device has to make sure that the clock line has been high for a given amount of time.

As for the communication itself a device writes its own address, as opposed to the target's address in I2C, followed by the information it wants to transmit. This way, all other devices on the net will be listening and they will know what device is broadcasting a message, allowing them to decide whether the message being sent is of interest to them or not.

Another difference is that in spite of having 8-bit communication, in LampCom there is no acknowledge bit. The reason for this is that since there is one device sending data to multiple devices at the same time, it wouldn't be possible to have all receiving devices acknowledging the data simultaneously. Figure 5 shows the way data is transferred between devices. Notice that because there is more than one byte being transmitted, it is necessary to have a start bit to synchronize devices. In this case, the start bit is when the data signal goes from high to low while the clock signal is stable in high state. This is the only situation where it is allowed for the data signal to change its state while the clock signal is high.

F. Test-bench

A test-bench was developed, which is intended to be a replica of a larger system, where the features of the system can be tested on a real world environment. This test-bench is shown in Figure 6. All the circuits for the illuminance sensor and to power the lamp are assembled and connected to each other according to Figure 7. The test-bench also features self-calibration using the LampCom's protocol.

Fig. 6: Picture of the test-bench that was assembled to evaluate the algorithms.

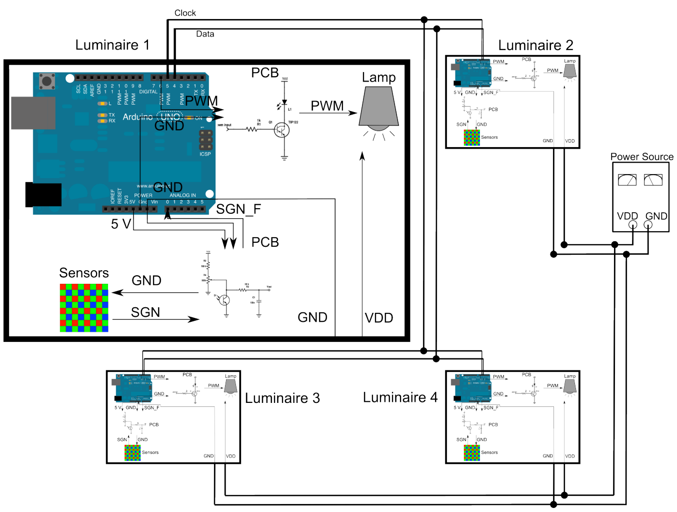


Fig. 7: Block diagram of the connections between all the circuit components and all the luminaires that are part of the test-bench.

V. Evaluation

This section covers the results of the most important tested algorithms on the simulation environment that was specifically developed for this purpose, as well as performances on the test-bench and in real world scenarios. All the performance indexes are presented as well as their behavior along time.

A. Simulation

The performance indexes on the simulation were studied for two different scenarios: one where the four studied workstations are evenly distributed throughout the room, which is an easier problem to solve, and one where the workstations are unevenly distributed and very close together, increasing the interactions between luminaires and making for a more difficult scenario. Occupancy states for each workstation were attributed randomly and external light influence was constant. Different scenarios for these two factors were not considered because they do not influence the algorithms' performance as much as the workstations' distribution, however they remained the same for every algorithm that was tested. The test duration is a relative time, sufficient for enough data to be extracted to compute the performance indexes. The results of these indexes are shown in Table III.

TABLE III: Table of comparison between different performance indexes for the most important algorithms that were tested under simulation. The results were obtained for two different scenarios: one where the distribution of the workstations was even, which represents a good scenario and one where the workstations are unevenly distributed, which represents a difficult scenario. The metrics represented in the table are energy consumption index, illuminance variation index and illuminance deviation index. The lower these indexes are, the better. In parentheses there is the negative relative error of the index in relation to the PID control so that smaller values, which are better, are shown with positive error.

Algorithm	PID	Automatic Learning
Even		
Energy (W)	2.91	2.85 (2.1 %)
Variation ($\mathrm{lx\,h^{-1}}$)	1599	1094 (31.6 %)
Deviation ($\mathrm{lx\,s^{-1}}$)	0.75	0.34 (54.7 %)
Uneven		
Energy (W)	2.57	2.5 (2.7 %)
Variation ($\mathrm{lx\,h^{-1}}$)	2433	1721 (29.3 %)
Deviation ($\mathrm{lx\,s^{-1}}$)	4.88	2.19 (55.1 %)

TABLE IV: Comparison of index performances of average energy consumption per luminaire, illuminance variation along time and average deviation along time for each of the control types tested on the test-bench. Inside parentheses is the negative relative error between the PID control's results and the distributed algorithm's results, so that a greater positive value represents a better performance.

Algorithm	Energy	Variation	Deviation
PID	2.30 W	7152 $\mathrm{lx\,h^{-1}}$	3.1 $\mathrm{lx\,s^{-1}}$
Distributed	1.98 W (13.9 %)	5783 $\mathrm{lx\,h^{-1}}$ (19.1 %)	3.1 $\mathrm{lx\,s^{-1}}$ (0 %)

The distributed algorithm with occupancy, predictive coupling matrix and error compensation (automatic learning) consistently performs better than the local PID control in both scenarios and in both energy consumption and in both user comfort indexes. In fact it is the only algorithm that is able to provide much lower energy consumption in both scenarios to that of the PID control but also have better user comfort throughout. Furthermore it has other capabilities, such as live exterior light influence compensation that other distributed algorithms do not have.

B. Test-bench

A comparison of the performance indexes is shown in Table IV, where it is also possible to compare the relative performance of each algorithm through the relative error inside parentheses. It is noticeable that the distributed algorithm has both lower energy consumption as well as better user comfort due to a lower variation of illuminance.

The results of both algorithms can be further compared by analyzing the illuminance along time in Figure 8a, where the main differences between the algorithms are:

TABLE V: Comparison of the performance indexes of the local PID control and the distributed algorithm with automatic learning when applied to a real-case scenario. Inside parentheses is the negative relative error of each performance index when compared to the PID control, where negative error represents a decrease in the parameter, which translates to better performance.

Algorithm	Energy (W)	Variation ($\mathrm{lx\,h^{-1}}$)	Deviation ($\mathrm{lx\,s^{-1}}$)
PID	3.62	1606	14.70
Distributed	3.67 (-1.38%)	1404 (12.6%)	3.32 (77.4%)

- Lower over-compensation of the distributed algorithm between time $50\,\mathrm{s}$ and $70\,\mathrm{s}$ of workstation 2 when workstation 1 changes its occupancy state. In fact, the over-compensation in the case of the local control is of $100\,\mathrm{lx}$ whereas in the distributed algorithm it is only of $40\,\mathrm{lx}$.
- The distributed algorithm has less ringing to the step response after time $70\,\mathrm{s}$ for both workstations.

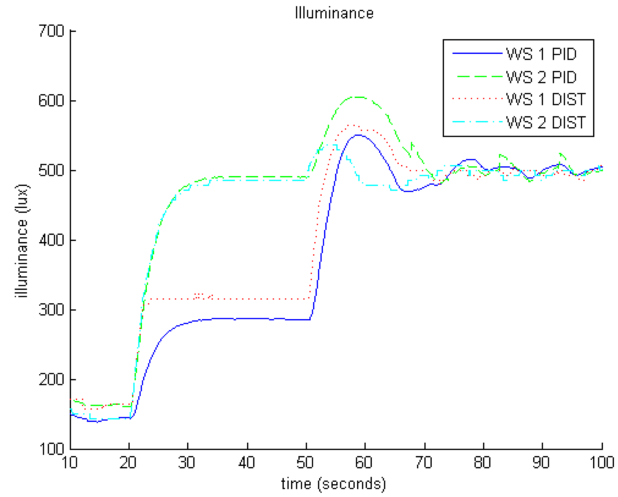
The difference between the duty-cycles of each algorithm in both workstations is shown in Figure 8b, where the most evident difference is that the distributed algorithm has a much more immediate compensation in workstation 2 to the change in occupancy state of workstation 1 at time $50\,\mathrm{s}$.

C. Application on a Real-case Scenario

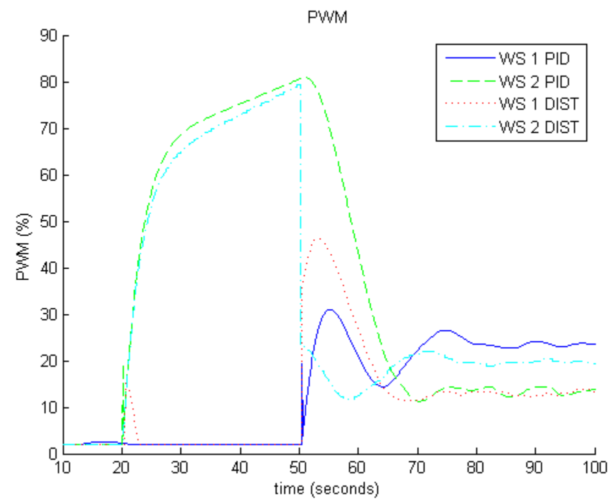
In order to establish the gains of a distributed smart illumination system on a real-case scenario, an experiment was developed. During the course of a workday on an office space without any smart illumination system, the state of two workstations, which were next to each other, was evaluated. Measurements were taken of their occupancy and illuminance. Afterwards, it was studied what the gains would be if a smart illumination system was installed during the same conditions. The gains of using a local PID control or a distributed algorithm with automatic learning are compared with the aid of the simulator. The performance indexes for both algorithms are presented in TableV.

Even though the PID control achieves a slightly lower energy consumption ($1.38\,\%$), it has a worse variation comfort index ($12.6\,\%$) and a poorer deviation index ($77.4\,\%$) which means that it does not comply more often to the $500\,\mathrm{lx}$ target than the distributed algorithm. This can easily be seen in the comparison Figure 9a for workstation 1 and Figure 9b for workstation 2, where every gray area is a period when the PID control is not compliant to the minimum $500\,\mathrm{lx}$ target. Because the slightly lower energy consumption of the local PID control is at the cost of lower comfort and not complying with the minimum illuminance standards, the distributed algorithm with automatic learning is deemed preferable.

Furthermore, the distributed simplex algorithm, which is one of the best performing smart illumination systems already in existence and which was already studied in section III states that an average power saving of $50\,\%$ was achieved for an average occupancy rate of also $50\,\%$ [13]. For this application on a real-case scenario on similar conditions but with an



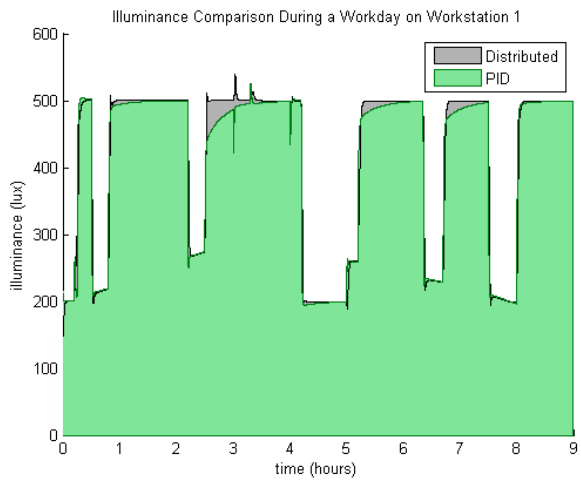
(a) Illuminance in lux along time for both the PID control and the distributed control on both workstations along the relative simulated time.



(b) Duty cycle of the PWM modulation along the relative simulated time for both the PID control and the distributed control running on the test-bench.

Fig. 8: Performance comparison of both the PID control and the distributed algorithm running on the test-bench, showing the illuminance and the duty cycle along time for workstation 1 using PID and the distributed control (WS 1 PID and WS 1 DIST, respectively) and workstation 2 also for both algorithms (WS 2 PID and WS 2 DIST).

average occupancy rate of $77\,\%$, which makes for a greater energy consumption, the distributed algorithm with automatic learning was actually capable of achieving power savings of $63.3\,\%$, which represents a reduction in consumed energy of $13.3\,\%$. Moreover, the algorithms studied in section III are not able to do live daylight harvesting, which means they cannot compensate for variations in external light influence, which inevitably varies. On the other hand, the distributed algorithm with automatic learning is not only capable of doing live daylight harvesting but it can also change its target illuminance throughout the day to replicate sunlight,



(a) Comparison of the illuminance in workstation 1 using a PID and a distributed algorithm.

(b) Comparison of the illuminance in workstation 2 using a PID and a distributed algorithm.

Fig. 9: Comparison of illuminance in lux between the PID control and the distributed algorithm with automatic learning throughout a workday.

thus creating even more comfort and the possibility for more workers' productivity.

VI. Cost Analysis

In order for the system to be economically beneficial, it has to be able to save more money by saving energy than its relative initial cost. To verify if this is true, an economical study must be undertaken.

A. *Bill of Materials*

The type of materials and the amount depends on the type of system that is being used. The bill of materials for each type of system and the cost of each material as sold by specialized retailers[34] is shown in Table VI.

[3]www.servelec.pt
[4]pt.farnell.com

TABLE VI: Bill of materials for each type of system (local control, centralized or distributed) and the cost of each material according to specialized retailers. Ticks represent the presence of the material on a certain system.

Item	Cost (euros)	Local PID	Centralized	Distributed
10 W LED Lamp	10	✓	✓	✓
Microcontroller	1	✓	✓	✓
PCB	1	✓	✓	✓
Sensors	1.5	✓	✓	✓
Electronics	0.5	✓	✓	✓
Cabling	1		✓	✓
Computer	400		✓	
Total		14	415	15

This means that the cost of implementing a centralized system is very costly because it needs a central processing unit to command the luminaires. However, the cost difference between the local control and the distributed control is minimal because the only difference between them is the cabling that connects the luminaires which in the case of a local control is not required.

B. *Energy and Power Cost Savings*

The following are the main variables that affect the power saving of the system:

- Daylight harvesting is the most influential factor for saving energy. This means that the amount of energy saved depends on the exterior light exposure of the system. The illuminance coming from sunlight varies according to the time of year, for example during summer the space may be more exposed to sunlight while during winter there is less external light illuminance. Other factors that may change the external light illuminance are the latitude and the number and direction of the windows on the space where the system is to be implemented.
- The amount of time workers spend in their workstations. The more time they spend away from them, the more gains the system will present.
- The power of the lamps used on the system. The more power the lamps have, the greater the benefits by using a smart illumination system.
- The cost of electricity. The more expensive the energy, the better will be the savings return of the smart illumination system.

Due to the fact that there are so many variables, it is necessary to take an example scenario and study the benefits of the system for such an example. The real-case scenario provides the perfect example for a case-study and cost comparison. In this system, the LED lamps necessary to provide the users with the appropriate illuminance for the tasks they perform have 10 W for each workstation. As for the cost of the electricity, an average price from a main electricity provider is $0.1570\,\mathrm{kW\,h}$ considering a simple counter and a hired power of $10.35\,\mathrm{kV\,A}$, which was the case of the company where the system was tested [19].

As was seen on section V-C the energy savings for a local PID control is $63.3\,\%$ and there is now enough data available to compute the cost benefits of a smart illumination system.

Taking into account an average workday of 9 hours (including lunch time), an average of 22 workdays every month and 12 months of work in a year, which is the case of the company studied, then a workstation's lamp is on for a total of $9 \times 22 \times 12 = 2376$ hours. Since the lamps in each workstation have $10\,\mathrm{W}$ each, then the total energy consumption is $10\,\mathrm{W} \times 2376\,\mathrm{h} = 23.76\,\mathrm{kW\,h}$. Since the system had energy savings of $63.8\,\%$, this equates to savings of approximately $0.63 \times 23.76 = 15.16\,\mathrm{kW\,h}$. Taking into account the cost of electricity considered, this means there is an annual cost saving per workstation of $15.16 \times 0.1570 = 2.38$ euros.

Considering that the increase in total cost to implement a distributed system is of 5 euros per workstation, excluding the LED lamp which is necessary even if no smart illumination system were to be implemented, then the return of investment would occur shortly after two years.

An engineering company is estimated at an average gross profit margin of approximately $60\,\%$ [5] which for a product cost of 5 euros makes a total retail cost of approximately 13 euros which translates to an expected return of investment from the customer of between 5 and 6 years, but of course this is just an estimate to evaluate the feasibility of the system.

VII. Conclusion

Illumination is one of the top energy consumers nowadays and therefore it is important to develop new techniques to enhance energy savings. Correct illumination of a work area can provide workers with better working conditions therefore making them more productive. One way to achieve this is to develop smart luminaires that adjust their light to the conditions (e.g. occupancy) and taking into account external light and neighbor lights. Several different solutions have been developed but none which associates the advantages of having reduced energy consumption while providing great user comfort at achieving an optimum solution.

For developing such an algorithm, a distributed control was deemed the most appropriate and it had several different ramifications before achieving the best performing one, which featured predictive coupling matrices and error compensation. This algorithm, which is also called distributed with automatic learning, was capable of achieving energy savings of approximately $60\,\%$ on the tests that it performed. These results are impressive not only because they represent a major energy saving but also because the algorithm performed better than already existing systems on the same conditions. With energy savings of this nature and taking into account the total cost of implementation and an average gross profit margin of a typical company on this sector, it means that it is possible to achieve a return of investment within 5 years, including profit margin.

While developing the algorithms, other tools had to be developed, not only to make the algorithms function properly but also to test them. An innovative communication protocol was devised, dedicated for distributed smart illumination systems which enables for many different devices to share the same bus without requiring master and slave devices. For properly analyzing the developed algorithms, innovative testing systems were conceived, which include a simulator with in-built light characteristics and a test-bench with a scaled model of an office space.

[5] http://research.financial-projections.com/

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