An intelligent lighting control system using photosensors placed on task area, controlling luminaires via LAN

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Abstract: - There exist a lot of alternatives to minimize energy consumption of artificial lighting systems. Daylight harvesting with the use of photosensors is one of the most usual methods to achieve energy savings and maintain visual comfort. Wireless sensor networks are a prominent technology to monitor a variety of environments and have plenty of applications in the field of lighting control. Conventional photosensors have a lot of disadvantages mainly because of their placement on the ceiling and their field of view. This paper reviews the applications of wireless sensor networks in lighting control, describes the drawbacks of the conventional photosensors and introduces a novel lighting control system, which controls the level of artificial lighting according to daylight penetration and users’ preference, using photosensors on the task area. The sensors are connected through PCs to the local area network using a controller. The controller receives the control signal from the photosensors and controls the light output of the luminaires by means of Digital Addressable Lighting Interface (DALI) protocol, through the local area network.

Key-Words: - daylight harvesting, network lighting control, photosensors

1 Introduction

It is common knowledge that lighting consumes a vast amount of energy in buildings. Researchers have proven that in office buildings, energy consumed by artificial lighting corresponds to 20-40% of the total energy consumption [1-3]. Plenty of alternative methods exist to reduce energy consumption in lighting while maintaining visual comfort. Daylight harvesting as well as modern lighting controls can contribute effectively to energy savings especially with the advent of LEDs which can provide long life times, dynamic lighting effects and greater design flexibility are flexible regarding their control.

The conventional photosensor is a complete control unit that consists of a light-sensitive photocell, input optics, an electronic circuit needed to convert the photocell signal into an output control signal and a housing and mounting device. Photosensors automatically adjust the output level of electric lights based on the amount of light detected. The objective of a photosensor is to provide the appropriate control signal in order for the luminaires to produce the required illuminance for the occupants of the room and at the same time contribute to decrease of energy consumption by dimming the artificial lighting system.
Many studies have researched the exploitation of daylight as well as the applications of photosensors in buildings and have proven significant energy savings. A research has quantified the energy savings by testing different electronic dimmable ballasts and performing simulations using a photosensor with different control algorithms [4]. One research has shown the potential of lighting energy savings in office spaces by using different control systems, for three locations in Europe and the four main orientations [5]. The method was based on simulations for daylight calculations, on laboratory experiments to evaluate energy consumptions and on the implementation of a new algorithm to simulate a feedback daylight dimming system. Savings varied from 45% to 61%. Another research has performed field measurements of high frequency dimming controls in atrium corridors [6]. Factors such as the electric lighting load, daylight availability and indoor illuminance were documented. It was found that the monthly electric lighting energy saving for the atrium corridors ranged from 14% to 65% using high frequency dimming controls. Another study has performed field measurements of a high frequency dimming control in an open plan office [7]. It was found that the estimated annual savings were 365 kWh, representing a 33% reduction in energy use for electric lighting under the dimming control in the office. Some researchers have monitored energy consumption in daylit, open-plan office areas in the New York Times Building with the application of digital addressable lighting controls and demonstrated that 28% energy savings can be achieved [8]. The subject of another study was to monitor energy consumption in 99 private offices in a 21-storey office building in California and to compare the energy savings from various lighting control alternatives, such as occupancy sensing, light level adjustment, manual dimming and daylighting [9]. The deduction of the research was that 20–26% of energy savings could be accomplished. A fuzzy controller that supervised the artificial lighting levels, was combined with a photosensor, a motion sensor and a light-pipe to optimize energy efficiency at an office in Istanbul, Turkey [10]. Another study has applied different control strategies (manual, independent and integrated) between shading and lighting control systems so as to quantify the energy saving and has proven the superiority of integrated lighting and daylight control to energy and visual performance [11].

2 Applications of wireless sensors in the field of lighting control

Wireless sensor network (WSN) technology was developed in the late 90’s and has received worldwide attention because of its many applications. A wireless sensor node comprises of a processor, memory, a power supply, a radio and an actuator. The radio is required for wireless communication so as to transfer the data from the sensors to a base station, since the sensors have limited memory and are typically installed in locations with limited access. A WSN typically has little or no infrastructure. It consists of sensor nodes cooperating in order to acquire data. Two types of WSNs exist: structured and unstructured. An unstructured WSN is one that contains a dense collection of sensor nodes. After the installation, the network is left unattended to monitor the environment and obtain any data required. The main disadvantage of an unstructured WSN is the complexity in its maintenance, because of the vast amount of nodes. In a structured WSN, all or some of the sensor nodes operate in a pre-organized manner. The advantage of a structured network is the lower network maintenance and management cost, since fewer nodes are deployed. Wireless sensor nodes are a prominent solution in order to monitor environments, where communication over physical wires could be expensive or even prohibited. Limitations regarding the resources of the network concern limited energy, short communication range as well as limited processing and storage in each node. Design constraints depend on the monitored environment. After all, the environment defines the size of the network and the network topology [12].

There exist a lot of references, which have examined the abilities of a network of photosensors along with efficient control algorithms so as to minimize energy consumption and at the same time meet the desired levels of illuminance.

A research study has incorporated various lighting control strategies, such as daylight harvesting, light level tuning and occupancy control, in open-plan offices with the installation of a wireless-networked sensing and actuation system, and a control algorithm to provide occupant-specific lighting. The proposed system dynamically adjusts the light output of each luminaire to meet each occupant’s requirements, while exploiting the available daylight. The system was modeled as a linear programming problem and an optimization algorithm provided the appropriate levels of dimming. The implementation of the lighting
control system has shown energy savings higher than 60% [13].

A study has proposed a novel utility-based building control strategy that optimizes the trade-off between meeting user comfort and reduction in operation cost by reducing energy usage. The system was based on a principled, decision theoretic formulation of the control task. A mobile wireless sensor network was used to optimize the trade-off between fulfilling different occupants’ light preferences and minimizing energy consumption with the exploitation of daylight. The proposed approach drastically increased the life of the wireless sensor network [14].

Another approach was the collaboration of occupancy sensors along with photosensors and the design of a multi-variable feedback controller to perform personal control with daylight and occupancy adaptation in a lighting system. User preferences were taken account in order to specify the sensor set-points. The centralized controller was designed by optimizing a weighted sum of squares of the illumination error and square of the power consumption, with illumination constraints at the light sensors and physical constraints on luminaire dimming levels. The performance of the proposed method was evaluated via simulations and compared with a benchmark stand-alone controller in an open-plan office lighting system. The results of the simulation could reach up to 45% energy savings [15].

A study has modeled a distributed algorithm for illumination control under local presence and light sensing, with networking constraints on exchanging control information. Each luminaire comprises of a LED light source which is dimmed by a local controller. The controller operates on the data it receives from a ceiling placed occupancy sensor and a photosensor. Finally, a communication module enabled the transmission of control information and the interconnection of the whole system. The proposed system was modeled as an optimization problem and sufficient conditions were provided under which the algorithm can achieve the target light sensor values. The performance of the distributed control algorithm was evaluated through simulations in an open office room. Significant energy savings, that reached up to 70% were demonstrated, when compared to the luminaires being at a fixed dimming level, with no presence or daylight adaptation [16].

A wireless sensor and actuator network was employed in a study. The light control system operated on feedback provided by the light sensors, which are carried by the users. Both whole and local lighting devices were considered. Two decision algorithms were proposed for the control of whole lighting devices and a surface-tracking scheme was designed for controlling local lighting devices. The proposed method was autonomous because it can adapt to environment changes and is independent from user’s current locations, as opposed to other systems. The algorithms were evaluated by running simulations using different configurations. However, the system had the following disadvantage: users had to carry light sensors to measure their current light intensities [17].

An iterative optimization algorithm that does not require accurate daylight knowledge for every iteration and produces smoother dimming level variations in luminaires was implemented in a recent study. The lighting system consisted of multiple luminaires, with integrated light and occupancy sensors and a central controller. The sensors transmit local occupancy state and illuminance measurements to the central controller, where dimming levels for the luminaires are optimized. Spatial uniformity of lighting and energy minimization were the basic goals of the proposed optimization [18].

3 Drawbacks of ceiling-based photosensors

The basic function of a photosensor is the production of a signal that is proportional to the amount and the distribution of incident lighting. The performance of the photosensor can be complex, because it depends on a lot of factors, such as:

- The distribution of daylight and artificial lighting in the space in which it is placed
- The spectral composition of lighting
- The adjustment settings of the commissioning control
- The ambient light level
- Its field of view

The location of the photosensor is significant to its operation. In theory, the ideal location of the photosensor would be on the working plane but until so far this position was avoided due to possible shading from occupants’ activity and the inability to power it without extra wiring. Thus, the behavior of a responsive daylight system in reality (sensor on the ceiling) can differ considerably from hypothetical cases, where the sensor is placed on the working plane.

A ceiling based photosensor reacts to incident radiation on the ceiling and converts this radiation to a proportional control signal. However, the ratio of ceiling/workplace illuminance is not stable since it
depends on the variation of daylight distribution in the room. Hence, it is difficult for a photosensor located on the ceiling to monitor accurately the illuminance changes on the working plane. This is the main drawback of a ceiling-based photosensor. The correlation of the lighting levels between these two positions relies on the location of the photosensor and its field of view. The optimum correlation can be achieved in areas away from windows, where light distribution is uniform. However, these areas could not be considered as daylight zones where daylight can be utilized ultimately. On the contrary, by placing the sensor near the window, increased energy savings are expected but with poorer performance in terms of achieving the design illuminance. The ability of the control system to maintain a constant ratio of ceiling photosensor to working surface illuminance can ensure the satisfaction of the operational equations of the control algorithms.

Furthermore, the spectral response of photosensors is wider than what the human eye sees. Thus UV and IR filters are fitted in front of photodiodes, but in most cases their response is still wider than the photopic human eye sensitivity V(λ). As a result photosensors perceive more light than human eye sees and artificial lighting is forced to be dimmed erroneously creating visual discomfort [19-20].

## 4 Proposal of an intelligent lighting control system with wireless photosensors on the task area

Taking into consideration all the above mentioned information from the review of the international bibliography, a new intelligent system with a wireless photosensor network is proposed. The system comprises of a set of individual photosensors that are placed on each task area (office) and are connected through the local area network, a controller that receives signal from the photosensors through the network and of course a set of luminaires that communicate with the controller using the DALI protocol. The controller calculates the appropriate dimming levels of the luminaires, which are the output of the proposed system, so as to satisfy a desired illumination objective, and transmits them back to the corresponding luminaires. The goal of the system is to provide the optimal light output for each office. The system has constant feedback, so as to adjust constantly the light output of the system to daylight levels and achieve maximum energy saving. A block diagram, that describes the function of the system, is presented below.

![Control diagram of the proposed system](image)

**Fig.1: Control diagram of the proposed system**

The first activity prior to the development of the system is to investigate all parameters that influence its operation (user behavior, spectral response of photosensor and spectral distribution of daylight and artificial lighting, operational equations for multiple photosensors, control strategy and communication of controller with lighting fixtures):

- Position, power supply and communication of each photosensor. Each photosensor can be a) positioned on the monitor of each computer, namely on each workplane area inside an office and b) powered via USB through a module that communicates wirelessly with the controller. Its technical characteristics (field of view, spatial and spectral response) can be examined with experiments. Figure 2 shows a USB-photosensor that will be used in this research.

![USB-photosensor](image)

**Fig.2: USB-photosensor**

- Calibration of the photosensor. A development of calibration set-ups and corresponding procedures can be performed. The above set-ups and calibration procedures will be standardized in order to be applied on any type/manufacturer of photosensors. Current standards define the desired lighting levels in a room which are expressed in illuminance values (lux). The photosensor will be calibrated to measure illuminance values with the highest possible accuracy in any conditions, when it is placed on the working plane.
• Spectral response. A spectral correction model that corrects the perceived illuminance from the proposed sensor will be developed in response to the CIE V(λ) photopic response, which simulates the spectral response of the human eye. For the corrections, a spectral hourly model can be created, which uses as inputs spectral measurements of lamps under various dimming levels. The spectral correction model converts the illuminance values that the photosensor perceives to a more accurate signal, based on the reflection characteristics of common materials, their color and texture characteristics, the spectral response of the photosensor, the spectral distribution of the incident daylight as well as the spectral transmittance of various glazing. All the above can be examined experimentally [21,22].

• Mathematical formulation and control algorithm. The European Norms recommend a minimum average illuminance value of 500 lux on the work plane level for office lighting [23]. A office task area, which is illuminated by m luminaires, can be transformed into a grid of n measurement points. The illuminance at a specific point of the workplane level (Ei), can then be represented as a sum comprising of the contribution of each luminaire on that measurement point (cij), multiplied by the corresponding dimming level of that luminaire (dj) and the contribution of the daylight (ui) to that specific point, as shown in Eq(1).

\[
\begin{bmatrix}
E_1 \\
E_2 \\
\vdots \\
E_n
\end{bmatrix} = \begin{bmatrix}
c_{11} & c_{12} & \cdots & c_{1m} \\
\vdots & \vdots & \ddots & \vdots \\
c_{n1} & c_{n2} & \cdots & c_{nm}
\end{bmatrix} \begin{bmatrix}
d_1 \\
d_2 \\
\vdots \\
d_m
\end{bmatrix} + \begin{bmatrix}
u_1 \\
u_2 \\
\vdots \\
u_n
\end{bmatrix}
\]

By minimizing the 1-norm of the vector d, the summation of the light output levels from each luminaire is minimized, which results into minimizing the energy usage of the artificial lighting system. The constraints regard the dimming levels of the system (from minimum to 100%) and the level of the illuminance, which should be equal or greater than 500 lux.

5 Conclusion
This paper reviewed the applications of wireless sensor networks to lighting control and presented important disadvantages of ceiling based photosensors. The most significant drawback of a ceiling based photosensor concerns its position and its inability to track accurately workplane illuminance. An intelligent lighting system is proposed, that overcomes the above mentioned obstacle. The sensors are installed on each office, namely on each PC monitor, providing the controller with accurate lighting levels of the workplane, which calculates the optimal dimming level for each luminaire and produces optimal localized lighting for each office.

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