ANNUAL JOURNAL OF ELECTRONICS, 2015, ISSN 1314-0078

Wireless Sensor Network-based Illumination Control

Marin Berov Marinov, Georgi Todorov Nikolov and Borislav Todorov Ganev

Abstract – **In this paper the problem of illumination control in a lighting system with networked lighting devices is examined. The luminaries have fluorescent light sources dimmable by a local controller. The optimal dimming values are calculated according to the user and legal requirements for illuminance of different workspaces and their actual illumination levels are measured by light sensors. A closed-loop lighting device control algorithm is used for obtaining the set illumination values. So a distributed and energy optimised illumination control with the use of daylight can be effectively implemented. The proposed approach is evaluated in lecture rooms and office environments.**

Keywords – **lighting control, daylight adaptive lighting, wireless communication, distributed lighting systems, LabVIEW.**

I. INTRODUCTION

Currently, electricity consumption for lighting in residential, commercial and industrial buildings accounts for about 15% of the total electricity consumption in the European Union. Over the past two decades, the lighting industry has developed new technologies that have greater potential for savings in lighting.

Innovative systems for indoor lighting can work over three times more efficiently than existing ones and with significant amounts of daylight, up to 75% of the electricity can be saved. Studies show that the full potential for energy saving can be realized only with the implementation of complex solutions using not only modern lighting, but intelligent control systems with sensors for light, motion, presence and others [1, 2, 3].

The use of wireless networks in the implementation of intelligent lighting systems is gaining ground as a promising approach. Numerous studies have shown the benefits of wireless sensor networks in the implementation of modern systems for lighting control [4, 5].

In recent years the application of wireless sensor networks for intelligent illumination control is becoming more popular. There are different illumination control approaches discussed in the literature depending on the architecture, connectivity and control strategies. Some of the first applications implemented on the basis of the DALI (Digital Addressable Lighting Interface) bus were presented in 2005 by O'Reilly et al. [6]. Park et al. defined some of the basic user requirements and their impact on energy efficiency [4]. Wen et al. presented an intelligent daylighting system with fuzzy rule-based sensor validation and fusion control [7].

The rest of this text has been organized in the following manner: Section II gives a brief overview of the standards for illumination levels in different workspaces. In Section III we propose a simplified system model and in Section IV the architecture of the intelligent illumination system. In Section V we present some experimental/prototyping results. The paper closes with Section VI, which summarizes the main points and provides an outlook for further work.

II. STANDARDS FOR INDOOR ILLUMINATION LEVELS

The leading international organization in the field of coordinating the management of lighting standards is CIE (Commission Internationale de l'Eclairage). The CIE has published a lot of recommendations for indoor lighting and contributed to the joint ISO-CIE standard ISO 8995-1 which deals with indoor working places [8]. CIE requirements have been interpreted in a different way in different countries. They are the basis for the current European standard EN 12464-1:2002: Light and lighting. Lighting of work places. Most recommendations in this standard include specifications about:

- Minimum illuminance levels on work planes;
- Minimum illuminance when working on computers;
- Minimum illuminance in the surroundings;
- Luminance ratios near task areas and some other parameters [9].

These specifications are essential and are related to the minimum quantities of light in the rooms and in task areas and surrounding areas, recommendations for glare etc. They are used to define the illumination levels in the different working zones and can be summarised as follows:

- The minimum illuminance levels on work planes for lecture rooms, offices, drawing and conference rooms vary from 200 to 500 lx.
- The recommendations concern the minimum horizontal and vertical illuminance levels, but do not take into account the luminance of computer screens.

III. MODEL OF THE SYSTEM

The proposed system assumes that the information about the presence or absence of users in the different zones and

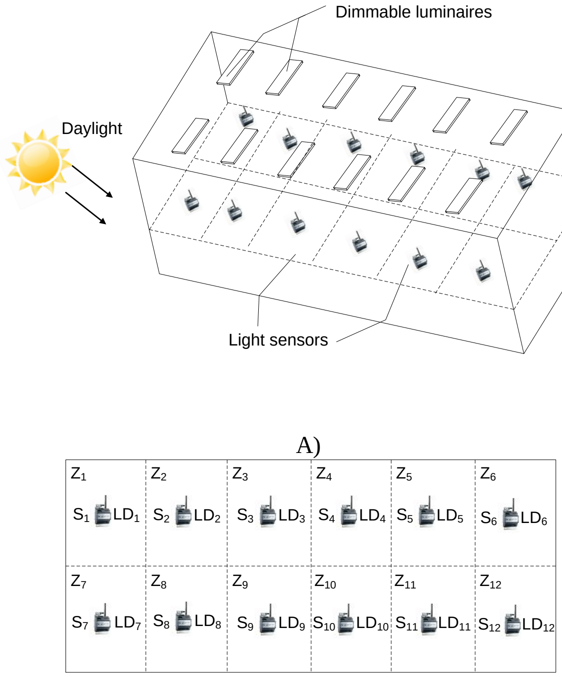
M. Marinov is with the Department of Electronics and Electronics Technologies, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8, Kliment Ohridski Blvd., 1756 Sofia, Bulgaria, e-mail: mbm@tu-sofia.bg

G. Nikolov is with the Department of Electronics and Electronics Technologies, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8, Kliment Ohridski Blvd., 1756 Sofia, Bulgaria, e-mail: gnikolov@tu-sofia.bg

B. Ganev is with the Department of Electronics and Electronics Technologies, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8, Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: b_ganev@tu-sofia.bg

the illuminance level that have to be achieved there is specified.

For the purpose of this study we use a (model of a) lecture room with N dimmable fluorescent lighting devices arranged in R rows and C columns. An example of such configuration with $N = 12$ lamps arranged in $R = 2$ rows and $C = 6$ columns is shown on Fig. **1**. The workspace plane is parallel to the ceiling and it is assumed that it is divided into the equal number N corresponding zones z_i, $i = 1 \dots N$. In each zone a light sensor s_i is mounted.



B)

Fig. 1. A) Model of a lecture room environment with networked lighting devices, B) Zoning scheme.

The lighting devices are labelled $LD_i, i = 1 \dots N$. They are networked over a DALI bus and have a fluorescent light source(s) and local dimming controller.

The dimming settings for each local controller are set so that the required illumination level in each zone is reached using gathered information about the illuminance in the corresponding zone and current dimming settings of the local and the neighbouring controllers.

A. *Illuminance measurement*

The sensors in the system periodically report the measured illuminance. The illuminance sensed by sensor $s_i, i = 1 \dots N$ is marked as $e(s_i)$. It has two basic components: luminance from the lighting devices and daylight.

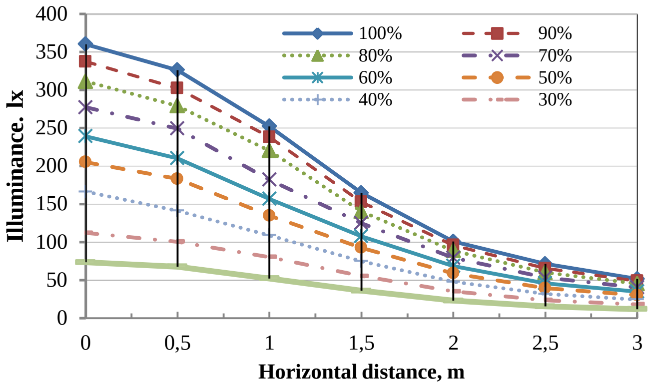
We denote with $e(LD_i)$, the component of the illuminance, contributed by device LD_i.

On the basis of the above notations for the purposes of simplification we can define the following vectors for the measured illumination and for the illuminance contributed by the lighting devices as:

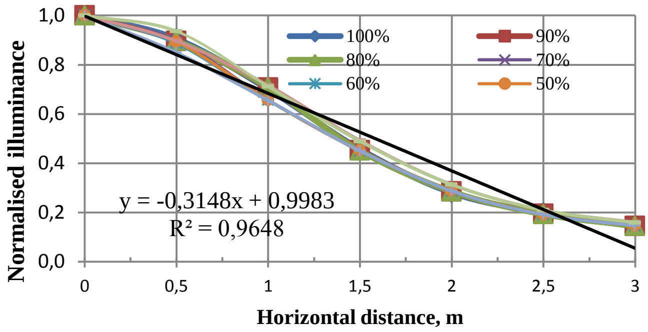
$$\begin{aligned} E_s &= [\, e(s_1), e(s_2), \dots, e(s_N)]^T \\ E_{LD} &= [\, e(LD_1), e(LD_2), \dots, e(LD_N)]^T \end{aligned} \quad (1)$$

B. *Computing E_{LD} and the dimming settings for the light sources*

The E_{LD} values cannot be determined directly. For estimating them we use an experimental approach proposed by Pan et al [10]. If there is only one lighting device switched on and there is no daylight we can measure the illuminance in the corresponding zone and in the neighbour zones at different distances with fixed sensors and a mobile sensor. It can be seen in Fig. 2.a that the illuminance measured by the sensor in the zone degrades with the distance in a coherent way with the different dimming settings (20 – 100%). Measured results can be normalised with respect to the maximum values for light at a horizontal distance of 0 m. After normalisation it can be seen that the degrading trends are almost the same. The dependence of degradation of the distance from the light source can be determined analytically with sufficient accuracy (using regression - see Fig. 2.b – linear trend line with coefficient of determination $R^2 = 0{,}9648$).



a) Measured illuminance



b) Normalised illuminance

Fig. 2. Experimental evaluation of illuminance degrading with the distance from the light source.

Using this experimental approach, if we assume that the impact factor of the lighting luminaire LD_i on the luminance sensed by the corresponding fixed sensor in the zone $e(s_i)$ is 1 ($w^i_{LD_i}$), the impact factors of LD_i on any other sensor $s_j, j = 1 \dots N$ can be defined as a weighted factor w^i_j, where ($0 \le w^i_j \le 1$). At the end we can achieve a normalised NxN Matrix W_N with all impact factors:

$$W_N = \begin{bmatrix} w_1^1 & w_1^2 & \cdots & w_1^N \\ w_2^1 & w_2^2 & \cdots & w_2^N \\ \vdots & \vdots & \ddots & \vdots \\ w_N^1 & w_N^2 & \cdots & w_N^N \end{bmatrix}. \quad (2)$$

Illuminance is additive and at a given point it is the sum of the illuminances from every luminaire in the room [11]. So the illuminance measured by the fixed sensor in every zone is the sum of the illuminances from the luminaire in the corresponding LD_i zone, from the neighbouring luminaires and daylight.

The daylight illuminance, measured by the fixed sensors can be written as $Nx1$ column vector E_{Day}. So the illuminance sensed by the fixed sensor can be written in a matrix form:

$$E_S = W_N \cdot E_{LD} + E_{Day}. \tag{3}$$

Equation (3) can be rewritten as

$$E_S - E_{Day} = W_N \cdot E_{LD} \Longrightarrow E_{LD} = W_N^{-1}\left(E_S - E_{Day}\right). \tag{4}$$

Here the normalised Matrix W_N with the impact factors can be measured a-priori at the design stage, the E_{Day} vector can be measured after switching all lighting devices off.

The computational complexity is $O = N \times N$ but can be significantly reduced because of the zoning concept used in lighting system design. It specifies that the luminaire significantly influences the illumination in the corresponding zone and a small area around it. As it can be seen in Fig. 1.b the LD_1 luminaire has a larger influence on zone z_1 than on zones z_2, z_7 and z_8. So, on the basis of the established dependence of illuminance degradation on the distance an appropriate threshold can be set and all impact factors bellow this threshold do not have to be calculated.

Finally, the dimming levels for all luminaires can be estimated on the basis of the calculated values for E_{LD}. The dimming levels are set via a set of standard DALI commands.

In the DALI standard the intensity of radiation is set by 8-bit integer. The 0 value means that the source is not switched on, 1 corresponds to 0.1% intensity and the value 254 corresponds to 100% intensity. The dependence of the light intensity of the set numeric value is logarithmic, but because of its specifics the human eye perceives it as linear [12]. It is assumed, that for each lamp a dimming value d is set. So for the j-th lamp the set value is given by d_j, where $0 \le d_j \le 254$. In case of N lamps we have a $N \times 1$ dimming vector for the light system given by

$$D = [d_1, d_2, \ldots, d_N]^T\ . \tag{5}$$

IV. Architecture of the Intelligent Illumination System

The system architecture and the main components of the implemented intelligent light control system are shown in Fig. **3**. It can be divided into three main parts: control host, lighting controller with DALI interface and wireless light sensor network.

A. Control host

The control host is implemented in LabVIEW programming environment. It consists of 3 main components:

1) User interface for system parameter configuration and wireless sensor network management and monitoring.

2) Sensor data handler for processing the sensor data and providing them to the control algorithms.

3) Dimmer handler which serves as the interface between the control host and the local dimming controller.

B. Lighting controller with DALI interface

In general, DALI is an industry standard that forms the basis for the unification of components and ensures full interchangeability of products from different manufacturers. In it each actuator has its own address, which receives commands and returns information about its current state. A significant advantage of the DALI system is the ability to obtain feedback about the operation of the light sources. As for the control function, it obtains feedback about: on/off state of the light source, lamp failure, absence of ignition, overheating ballast defects and other faults of the luminaires. Data is transmitted via a dedicated two-wire line with the maximum length between two devices not exceeding 300 m. The interface is bidirectional with a data transfer speed at 1,2 kbps.

A lighting controller is implemented and it is based on programmable logic controller 750-881 of the WAGO company and is equipped with 750-641 DALI / DSI module [13]. Its main tasks are to set the appropriate dimming levels and to obtain feedback about the operation of the light sources.

C. Wireless light sensor network

Our sensor nodes are developed using NI-WSN9791for the wired part of the communication and NI-WSN3202 for the wireless part together with an integrated Ambient Light Sensor TEMT6000 [14].

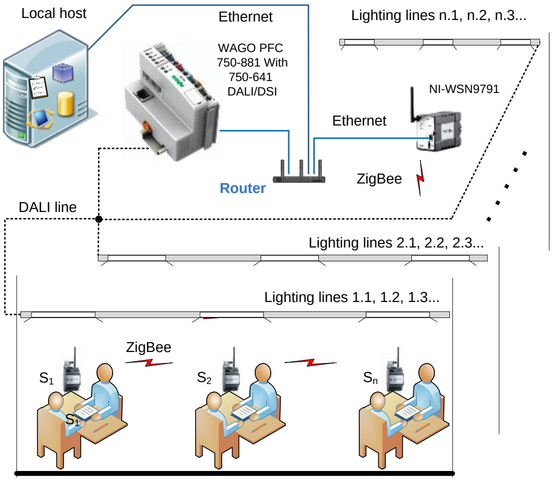


Fig. 3. System architecture.

V. Prototyping Results

In order to illustrate the applicability and capacity of the wireless system presented here, a number of experiments were done.

The LabVIEW block diagram of the software implemented for WSN and illumination control is shown in Fig. 4. In this work the producer/consumer design pattern is selected as base software architecture. This design pattern is a pre-designed solution which separates the two main components by placing a queue between different loops, which allows the producers and the consumers to execute in different threads. With the producer/consumer design pattern the user can easily handle multiple processes running at different speeds. Communication between the processes is buffered using data queues.

In Fig. 4 the upper loop acts as a producer. In the upper left corner of the Event Structure is positioned a Shared Variable AIO, which communicates with one of the wireless modules. In this Shared Variable is stored the current measured data of illuminance. If the measured illuminance value is greater than desired, the producer loop "enqueued" command and data to the consumer loop to decrease the intensity of radiation of a luminaire and vice versa.

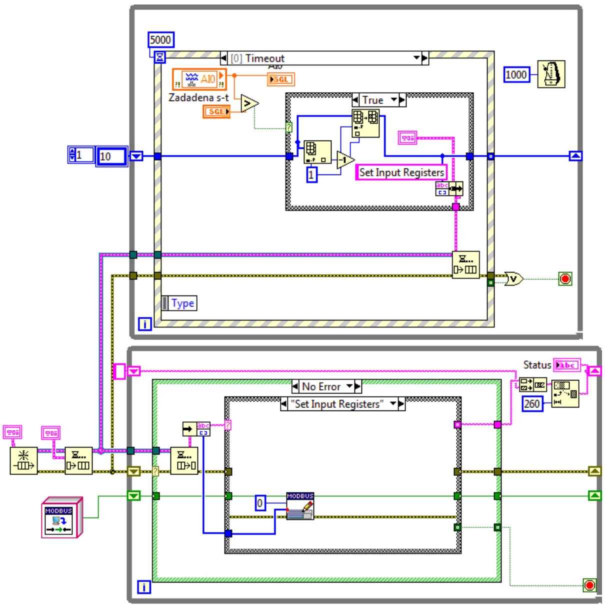


Fig. 4. The LabVIEW block diagram for WSN control and Modbus communication.

The lower loop acts as a consumer and its main function is to provide communication information via the DALI interface. The communication is developed by a set of functions from Modbus Library for LabVIEW programming environment. This library consists of a number of Virtual Instruments that provide communication from any standard Ethernet port, implement тхе Modbus software protocol and offer functionality to both, master and slave. Fig. 5 shows one of these Virtual Instruments that writec тхе data into тхе input registers of a Modbus device.

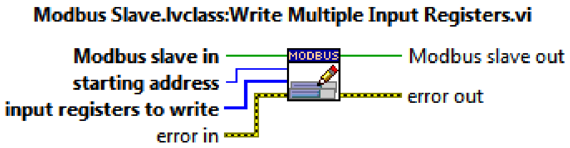


Fig. 5. A Virtual Instrument from Modbus Library for LabVIEW

VI. CONCLUSION

The combination of optimizing user comfort, meeting illumination levels requirements and employing strategies for energy saving is a task of an enormous economic importance. In this paper we presented a WSN-based illumination control system based on the zoning concept and daylight use. On the basis of the device control and illumination control algorithms presented here the required illumination levels in the different zones can be dynamically controlled and energy consumption optimised. The proposed hardware solutions are verified by real implementation in a lecture hall environment. The experimental results verify the feasibility of the presented approach.

REFERENCES

[1] F. Rubinstein, M. Siminovitch, and R. Verderber, "Fifty percent energy savings with automatic lighting controls," IEEE Transactions on Industry Applications, vol. 29, no. 4, pp. 768-773, 1993.

[2] K. Topp, „Effiziente und innovative Beleuchtung Potenziale, Beispiele und Trends,“ Fachverband Licht im ZVEI, 2012.

[3] T. Atanasova, T. Tashev, “Analysis and Evaluation of Energy Losses in Living Environment on the Basis of Cognitive-Expert Classification,” Problems of Engineering Cyberneticg and Robotics, vol. 64, pp. 11-18, 2011.

[4] H. Park, M.B. Srivastava, J. Burke, “Design and Implementation of a Wireless Sensor Network for Intelligent Light Control. in In Proc.eedings of the 6th Int. Symposium on Information Processing in Sensor Networks, IPSN’2007, Cambridge, MA, USA, 25–27 April 2007.

[5] W. Y. Lun; Che, Y. L.; Chi, W.K.; Yu, C. T.; Chih, W. Y., “Autonomous light control by wireless sensor and actuator networks,” IEEE Sens. Journal, no. 10, pp. 1029-1041, 2010.

[6] F. O’Reilly, J. Buckley, “Use of Wireless Sensor Networks for Fluorescent Lighting Control with Daylight Substitution,” in Proc. Workshop on Real-World Wireless Sensor Networks, Stockholm, Sweden, 2005.

[7] Y.-J. Wen, J. Granderson, and A. M. Agogino, “Towards Embedded Wireless-Networked Intelligent Daylighting Systems,” in Proc. IEEE Int. Conf. Sensor Netw. Ubiquitous Trustworthy Comput., 2006.

[8] Standard CIE S 008/E: 2001/ISO 8995-1:2002(E): Lighting of Work Places - Part 1: Indoor, 2002.

[9] Standard EN 12464-1:2002: Light and lighting- Lighting of work places- Part 1: Indoor Work Places..

[10] M. S. Pan, L. W. Yeh et al., “A WSN-Based Intelligent Light Control System Considering User Activities and Profiles,” IEEE Sensors Journal, VOL. 8, NO. 10, vol. 8, pp. 1710-1721, 2008.

[11] O. Ransen, Candelas Lumens and Lux, Ransen Software, 2014.

[12] “Digital Addressable Lighting Interface,” [Online]. Available: http://www.dali-ag.org.. [Accessed 2014].

[13] “WAGO-I/O-SYSTEM 750 ETHERNET TCP/IP Programmable Fieldbus Controller 750-842,” WAGO Kontakttechnik GmbH & Co. KG, 2010. [Online]. Available: www.wago.de.

[14] V. Semiconductors, "Ambient Light Sensor TEMT6000," 2011.

[15] C. DiLouie, Advanced Lighting Controls: Energy Savings, Productivity, Technology and Applications, 1 ed., Fairmont Press, 2005.

[16] “Application Report, Digital Addressable Lighting Interface (DALI) Implementation Using MSP430 Value Line Microcontrollers,” [Online]. Available: http://www.ti.com/lit/an/slaa422a/slaa422a.pdf. [Accessed March 2014].