知的照明システムにおける照度と色温度制御

Illuminance and Color Temperature Control in Intelligent Lighting System

鮑　新平[*]　　張　光磊[*]　　鄭　継川[*]

Xinping BAO　　Guanglei ZHANG　　Jichuan ZHENG

要　旨

一般に，照度と色温度の組み合わせによる照明システムは，異なる色温度を有する異なる照明源の照度に基づき色温度を比例配分し制御している．この技術は，各光源の色温度が照度に対して一定であると仮定している．しかし，この仮定は，実際には常に成立するとは限らない．複数の照明源がある環境では，従来の照明システムでは，結果が目標値とは大きく異なる可能性がある．

したがって，我々は複数の照明源の色温度と照度制御の問題を明らかにし，これに対処するために，新たなライティングモデルを構築することによって照度と色温度制御システムを開発した．

本論文では，照明システムを構成するそれぞれの単色光源（RGB LED）からの調光レベルに対応するCIE XYZ三刺激値を測定することで，照度と色温度の制御モデルを構成する．さらに，調光レベルに対する色温度と照度の変化の割合を利用することにより，測定対象位置においてどのように明るさと色温度が変化するのかを知ることができる．さらに二次計画法により，ユーザーの快適性を損なわない範囲でエネルギー消費を最小にすることができる．

ABSTRACT

Combination control of illuminance and color temperature is generally based on proportionally mixing different lighting sources with different color temperature, which assumes that the color temperature of each lighting source is invariant to the luminous levels. However, this assumption does not always hold true in reality. In multiple lamps environment, the above mentioned technique might lead to large difference comparing with target values.

Therefore, we have developed an illuminance and color temperature control system by constructing a lighting model to address the problem of color and illumiance control for multiple lamps cases.

This paper builds an illuminance and color temperature model by measuring CIE XYZ tristimulus values corresponding to the dimming level of each monochrome lamp (e.g. RGB LED). Furthermore, through extracting the gradient information of color temperature and illuminance with respect to the dimming levels, we can know where the lighting should be darker/brighter and how to change the color temperature at that place. Finally by using quadratic programming technology, we can meet user requirements with minimum energy consumption.

* リコーソフトウェア研究所（北京）有限公司
Ricoh Software Research Center (Beijing) Co., Ltd.

1. Introduction

With the current movement toward greener and more sustainable buildings, numerous research work is focusing on illuminance and color temperature control since they have great effect on office workers[1,2]. The research results[3] indicate that sensor-based lighting control system generated substantial energy savings and peak power reductions compared to a conventional fluorescent lighting system. The installed lighting power is 42%-47% lower than that of the conventional system. It has reported that proper changes in illuminance and color temperature corresponding to biological rhythm can enhance intellectual productivity in an office environment[4,5]. A field study[6] in industrial environment measures directly the productivity increases ranging from 0 to 7.7% caused by color temperature changes in lighting. In addition, it has been studied that individual workers may need different illuminance for different activities[7]. Even for the same activity, the requirements on luminous environment of different workers are different.

RGB-LEDs have the ability to change the illuminance and color temperature simultaneously by adjusting the dimming level of each monochrome channel in addition to many other advantages such as longer lifetime. Therefore, they have great potential in office illumination for enhancing workers' productivity.

Generally, combined control of illuminance and color temperature is based on proportionally mixing different lighting sources with different color temperature. However, it is difficult to obtain desired illuminance and color temperature through simple dimming level control for multicolor LED-based lighting fixtures due to

(1) linear hypothesis between illuminance and dimming levels

(2) constant color temperature hypothesis over dimming level adjustment.

For example, a linear model is built between dimmers and illuminance measurement and a PID controller is designed to regulate the desired illuminance[8]. The simulation results have shown good performance at nominal level condition. However, it gets worse when control level deviating from the nominal level. Tomishima et al. have developed a distributed intelligent lighting control schemes to provide user-defined illuminance and color temperature at specific locations[2]. For system modeling and control, they use adaptive neighborhood algorithm and simulated annealing algorithm respectively. However, the distributed system suffers from longer convergence times due to data fusing compared to centralized schemes.

This paper focuses on developing an illuminance and color temperature control system to meet the requirements of illuminance and color temperature in different regions with minimum energy cost. Piecewise linear method is used to obtain lighting model. The method enables our controller to work properly at any level of light amount. For the control scheme, quadratic programming is employed for minimizing energy consumption subject to satisfying user preferences.

The remainder of the report is organized as follows. In Section 2, a framework of intelligent lighting control is described. In Section 3, correlated color temperature (CCT) and illuminance models are built. A controller is designed in Section 4. Simulation results are shown in Section 5. Summary and future works are given in Section 6.

2. Framework of intelligent lighting system

The framework of intelligent lighting system combining the control of color temperature and illuminance is shown in Fig.1. Basically, the framework comprises of four modules: target lighting setting module, color sensing module, lighting controller module and lighting apparatuses module. The lighting apparatuses here refer to the devices whose color temperature and illuminance can be adjusted through changing of dimming levels.

For the implementation of the lighting control system, firstly, the target values of illuminance and color temperature are set by means of wireless devices. Next, the color sensing module measures illuminance and CCT at task areas. Then the controller module optimizes the dimming level of the lighting module to minimize this difference. The controller output (dimming level signals) will be sent to the lighting apparatuses module by means of wireless LAN (Local Area Network).

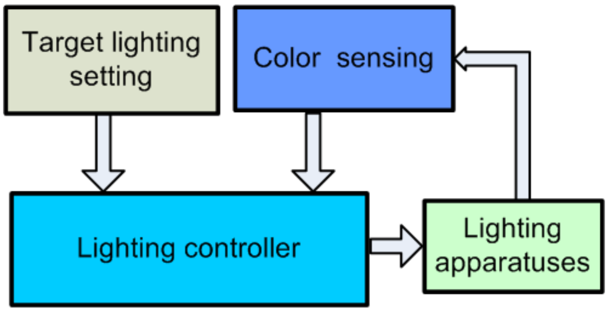

Fig.1 Framework of lighting control system.

3. CCT and illuminance model

3-1 CCT model

The proposed model of CCT is based on McCamy's polynomial model[9] in Eq.(1), which can be implemented with simple operations on XYZ tristimulus.

$$
\begin{aligned}
CCT &= f(x,y)\\
&= 449\left(\frac{x-0.332}{0.1858-y}\right)^3 + 3525\left(\frac{x-0.332}{0.1858-y}\right)^2 + \\
&\quad 6823.3\left(\frac{x-0.332}{0.1858-y}\right) + 5520.33
\end{aligned} \tag{1}
$$

Where

$x = X/(X+Y+Z), y = Y/(X+Y+Z)$. *X*, *Y* and *Z* are tristimulus values of combined light. Since the CCT is the function of the chromaticity *x* and *y*, while *x* and *y* are the function of tristimulus values of *XYZ*, so if the relationship between *XYZ* and dimming values is found, CCT can be calculated according to dimming values of lamps.

To identify the relationship of XYZ tristimulus values according to dimming level at a given region, assume the working plane of office is divided into *N* regions. For an arbitrary region *j* (*j* = 1, 2, …, *N*) at working plane, the relationship of tristimulus values according to dimming level D of each lamp *i* (*i* = 1, 2, …, *n*) is formalized as:

$$
\begin{aligned}
X_j^{(i)} &= g_j^{(i)}(D_i)\\
Y_j^{(i)} &= h_j^{(i)}(D_i)\\
Z_j^{(i)} &= p_j^{(i)}(D_i)
\end{aligned} \tag{2}
$$

Eq.(2) can be identified by linear regression analysis. Based on Grassmann's additivity law, the XYZ tristimulus combined all lights at arbitrary position *j* can be formulated as summation of independent coordinates $X_j^{(i)}$, $Y_j^{(i)}$ and $Z_j^{(i)}$ of light *i* (*i* = 1, …, *n*):

$$X_j = \sum_{i=1}^{n} X_j^{(i)} = \sum_{i=1}^{n} g_j^{(i)}(D_i) \tag{3-1}$$

$$Y_j = \sum_{i=1}^{n} Y_j^{(i)} = \sum_{i=1}^{n} h_j^{(i)}(D_i) \tag{3-2}$$

$$Z_j = \sum_{i=1}^{n} Z_j^{(i)} = \sum_{i=1}^{n} p_j^{(i)}(D_i) \tag{3-3}$$

Let dimming level signals of all lights be defined as:

$$D^T = [D_1 \quad D_2 \quad \ldots \quad D_n] \tag{4}$$

The derivative of CCT function with respect to dimming value of lamps at region *j* can be easily obtained:

$$\frac{dCCT_j}{dD} = \frac{\partial f(x,y)}{\partial x}\frac{\partial x}{\partial X_j}\frac{\partial X_j}{\partial D} + \frac{\partial f(x,y)}{\partial x}\frac{\partial x}{\partial Y_j}\frac{\partial Y_j}{\partial D}$$
$$+ \frac{\partial f(x,y)}{\partial x}\frac{\partial x}{\partial Z_j}\frac{\partial Z_j}{\partial D} + \frac{\partial f(x,y)}{\partial y}\frac{\partial y}{\partial X_j}\frac{\partial X_j}{\partial D} + \quad (5)$$
$$\frac{\partial f(x,y)}{\partial y}\frac{\partial y}{\partial Y_j}\frac{\partial Y_j}{\partial D} + \frac{\partial f(x,y)}{\partial y}\frac{\partial y}{\partial Z_j}\frac{\partial Z_j}{\partial D}$$

The change of CCT corresponding to dimming level of all lamps is presented as:

$$\Delta CCT_j = \frac{dCCT_j}{dD}\Delta D \quad (6)$$

where $\frac{dCCT_j}{dD}$ is an *n* x 1 vector.

Since CCT variable can be measured at each time step, we use the following discrete-time system as the "real" system in the simulations:

$$CCT_j(t+1) = CCT_j(t) + \Delta CCT_j$$
$$= CCT_j(t) + \frac{dCCT_j}{dD}\Delta^{(t)} \quad (7)$$

where

$$\Delta^{(t)} = D(t+1) - D(t) \quad (8)$$

and $CCT(t)$ is the color temperature sample at the *t*-th sampling instant. If given the sampling interval *Ts*, $CCT(t)$ means the CCT after *tTs* passed. With Eq.(7) the CCT model with dimming level of lamps is achieved.

3-2 Illuminance model

Since the tristimulus value *Y* indicates the illuminance value *E*, the illumination $E_j^{(i)}$ at arbitrary position *j* can be formulated as:

$$E_j^{(i)} = Y_j^{(i)} = \sum_{i=1}^{n} h_j^{(i)}(D_i) \quad (9)$$

The derivative of illuminance function with respect to dimming value of lamps can be obtained:

$$\frac{dE_j}{dD} = [\frac{dE_j^{(1)}}{dD_1} \quad \frac{dE_j^{(2)}}{dD_2} \quad \cdots \quad \frac{dE_j^{(n)}}{dD_n}] \quad (10)$$

The change of illuminance *E* of combined illuminance around the given dimmer level D is:

$$\Delta E_j = \frac{dE_j}{dD}\Delta D \quad (11)$$

So the measurements of illuminance at time *t* +1 can be estimated as:

$$E_j(t+1) = E_j(t) + \Delta E_j(t)$$
$$= E_j(t) + \frac{dE_j}{dD}\Delta(t) \quad (12)$$

Eq.(12) is the illuminance model we need. In practice application, the coefficient $\frac{dE_j^{(i)}}{dD_i}$ in equation (12) can be calculated with equation (13):

$$\left.\frac{dE_j^{(i)}}{dD_i}\right|_{D_i} = \frac{h_j^{(i)}(D_i(t+1)) - h_j^{(i)}(D_i(t))}{D_i(t+1) - D_i(t)} \quad (13)$$

4. Controller design

To meet different illuminance and color temperature requirements as well as minimizing energy consumption for different task applications or user preferences, the lighting controller is formalized as a problem to find:

$$\Delta(t) = [\delta_1 \quad \delta_2 \quad \ldots \quad \delta_n]^T \quad (14)$$

such that minimizes the objective function *J*:

$$\min J = \begin{Bmatrix} \beta\sum_{j=1}^{N} w_j^E [(E_j(t) - \bar{E}_j + \frac{dE_j}{dD}\Delta(t)]^2 + \\ \gamma\sum_{j=1}^{N} w_j^K [CCT_j(t) - \overline{CCT_j} + \frac{dCCT_j}{dD}\Delta(t)]^2 \\ + ([D+\Delta(t)]^T P_L)^2 + \alpha\|\Delta(t)\|^2 \end{Bmatrix}$$

$$subject \quad to \quad 0 \le D + \Delta(t) \le 1$$
(15)

where

$\overline{E}_j$: target illuminance at task area *j* of working plane

$\overline{CCT}_j$: target CCT at task area *j* of working plane

w_j^E : illuminance weight at task area *j* of working plane

w_j^K : CCT weight at task area *j* of working plane

β : a relative weighting on illuminance performance

γ : a relative weighting on CCT performance

α : a relative weighting on dimming level size.

P_L : a vector of lamps' maximum power consumption.

D: dimming level signals of lamps.

$\sum_{j=1}^{N} w_j^E([(E_j(t) - \overline{E}_j + \frac{dE_j}{dD}\Delta(t))^2$ is the summation of illuminance difference square. The aim of this term is to minimize the difference between the reference and model outputs which is shown in Eq. (12).

$\sum_{j=1}^{N} w_j^K(CCT_j(t) - \overline{CCT}_j + \frac{dCCT_j}{dD}\Delta(t))^2$ is the summation of color temperature difference square. The aim of this term is to minimize the difference between the reference and model outputs which is shown in Eq. (7).

$[D + \Delta(t)]^T P_L$ is total power consumption.

$\|\Delta(t)\|^2$ is the control energy which is proportional to the consumption of electric energy.

The solving of Eq.(15) can be taken as a quadratic programming problem with inequality constraints.

5. Simulation results

5-1 Simulation environment

An office room model shown in Fig.2 is constructed by DIALux lighting simulation software. The layout of office room is 6.3x4.2x2.3m (*L*x*W*x*H*). The luminaires in lighting simulation is Philips BCS680 W7L122 1xLED24/840 (power: 28W, luminous flux: 1650 lx).

Fig.2 Room model by DIALux.

The blue and red circles shown in Fig. 3 indicate the positions of light sources in this simulation, where the small blue circles are the lamps for providing constant background lighting, and the thick red ones with number from 1 to 6, providing dimmable task lighting. The red ones are controllable in the simulation.

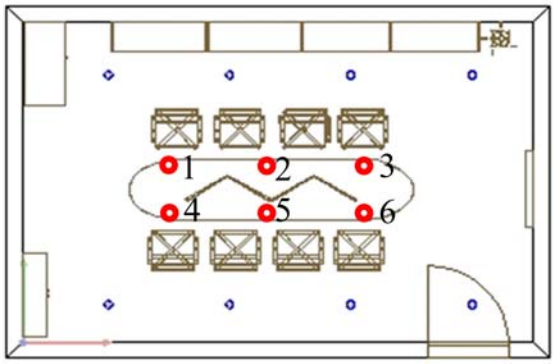

Fig.3 Positions of light sources in the simulation.

In current lighting simulation software, CCT measurement is unavailable since there is no color temperature profile library. In this simulation, we will focus on illuminance simulation only. Therefore, the controller we validated is only about illuminance. The Eq.(15) is simplified as:

$$\min\ J = \{\ \beta_1 \sum_{j=1}^{N} w_j^E [(E_j(t) - \overline{E}_j + \frac{dE_j}{dD}\Delta(t)]^2 + $$
$$\beta_3([D+\Delta(t)]^T P_L)^2 + \alpha\|\Delta(t)\|\ \} \quad (16)$$
$$subject\ to\ \ 0 \le D + \Delta(t) \le 1$$

To validate our controller design, a scene with 3 persons who have individual illuminance preferences is designed as shown in Fig.4.

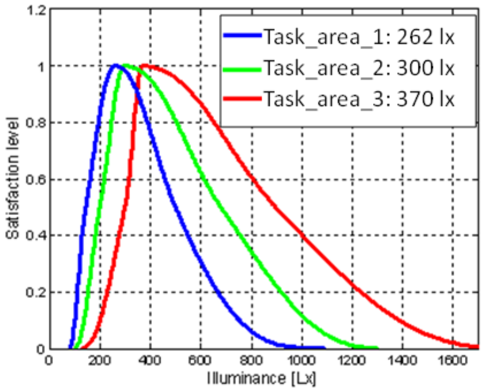

Fig.4 Illuminance preference.

To better display the results of simulation without blocking users' illuminance, users' task areas are designed in three different regions as shown in Fig.5. Fig.2 is just a visualized demonstration to show the scene. The purpose of such an assignment is to better display the results of simulation without blocking users' illuminance.

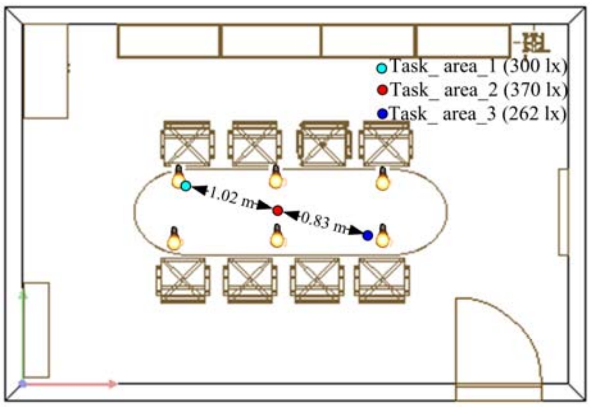

Fig.5 Distribution of task areas.

The reference illuminance distribution is shown in Fig.6. The reference illuminance distribution follows the country standards on illuminance such as: i) Specifications for illuminance uniformity on the task area. ii) Specifications for luminance ratio between task and immediate surroundings.

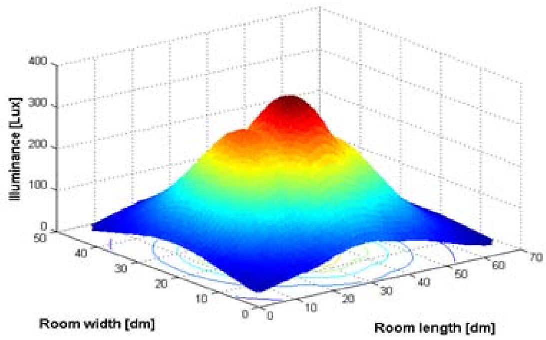

Fig.6 Reference of illuminance distribution.

5-2 Simulation results

In initial lighting environment before lighting control, all lamps nearly work at a full ON state shown in Fig 7.

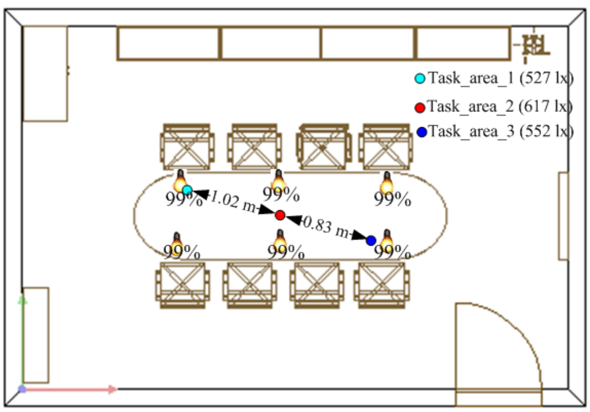

Fig.7 Initial states of lamps.

A large illuminance difference comparing with reference illuminance distribution is shown in Fig.8.

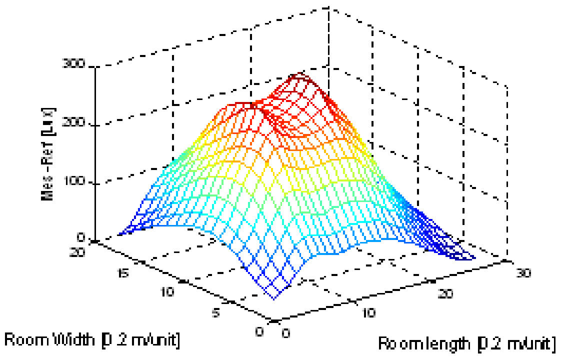

Fig.8 Illuminance difference before control.

After runing illuminance controller, the illuminance difference distribution are show in Fig.9. The updated dimming value of all lamps are shown in Fig.10.

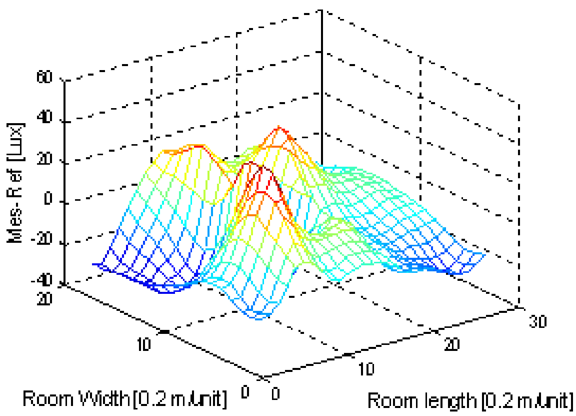

Fig.9 Illuminance difference distribution after 1st control.

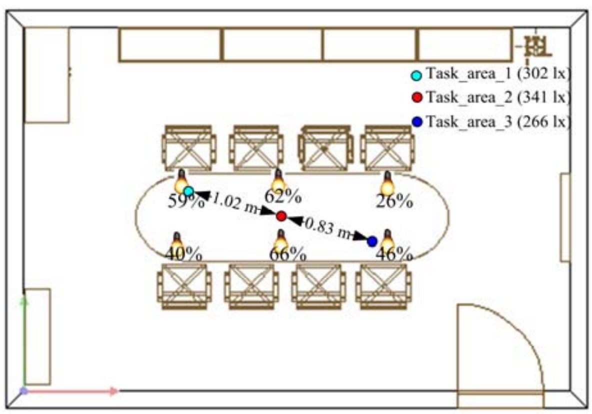

Fig.10 Updated dimming signal state.

Comparing the illuminance of task areas in Fig.8-9 with the reference shown in Fig.6, RMSs (Root Mean Square) are 256.01 lx and 16.94 lx respectively. The Standard deviations are 32.19 lx and 18.50 lx respectively. RMS residual at task areas reduced 93.38 % comparing with the result of before control. We can see that illuminance at working plane is significantly improved by the implementation of illuminance controller.

In our experiment, the dimming values generated by intelligent controller are set again in DIALux simulator to adjust current lighting state. Fig.11 shows the dimming level signal evolution via control rounds. The Numbered lamps are corresponding to the lamp order as shown in Fig.3. It can be seen that our control algorithm has numerical stability for a given reference illuminance.

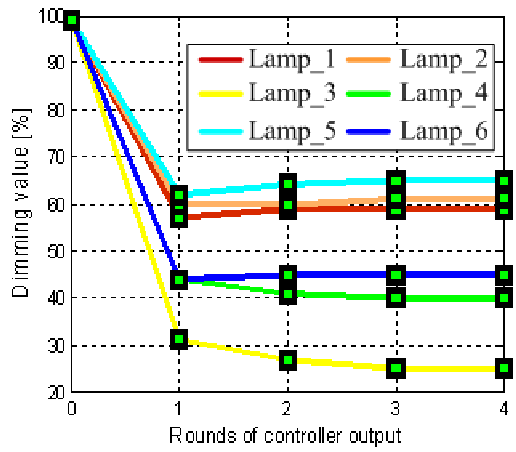

Fig.11 Evolution of dimming level signals.

6. Summary and future works

6-1 Summary

In this report, we have constructed a framework of intelligent lighting control system and proposed an algorithm to control CCT and illuminance, wherein, illuminance control is verified by DIALux simulator. To summarize, this lighting control system has the following features:

(1) Both illuminance and CCT models are only related to the dimming levels of lamps. XYZ tristimulus values of lights just act as an intermediate between CCT and dimming levels.

(2) Illuminance/CCT difference at each task area is related to the corresponding weight of that task area. The larger weight of a task area, the smaller illuminance/CCT difference at that task area we will get.

6-2 Future works

In next stage, a real experiment environment with CCT and illuminance measurement will be built to verify combined CCT and illuminance control algorithm.

References

1) L. W. Yeh et al.: Y Autonomous light control by wireless sensor and actuator networks, *IEEE Trans. sensors*, Vol.10, Issue. 6, pp.1029-1041 (2010).

2) C. Tomishima et al.: Distributed Control of Illuminance and Color Temperature in Intelligent Lighting System, *Proc. 10th International Conference on Artificial Intelligence and Soft Computing*, Vol.6114, pp.411-419, Springer (2010).

3) AD Galasiu et al.: Energy saving lighting control systems for open-plan offices: A field study, *Leukos*, Vol.4, NO.1, pp.7-29 (2007).

4) Obayashi et al.: Development of an illumination control method to improve office productivity, *Proc. 12th International Conference on Human-Computer Interaction*, Vol.9, No.2, pp.939-947 (2007).

5) H. Juslén: Influence of the colour temperature of the preferred lighting level in an industrial work area devoid of daylight, *Ingineria Iluminatului*, Vol.8, No.18, pp.25-36 (2006).

6) H. Juslén: Lighting, productivity and preferrd illuminances-field studies in the industrial environment, Thesis (PhD), Helsinki University of Technology (2007).

7) P. Boyce, N. Eklund, N. simpson: Individual lighting control: Task, performance, mood, and illuminance, *Journal of the Illuminating Engineering Society*, Vol.29, No.1, pp.131-142 (2000).

8) R. D. Keyser, C. Lonescu: Modelling and simulation of a lighting control system, *Simulation modeling practice and theory*, Vol.18, pp.165-176 (2010).

9) C. McCamy: Correlated Color Temperature as an Explicit Function of Chromaticity Coordinates, *Color Research & Application*, Vol.17, pp.142-144 (1992).