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Lighting system design based on a sensor network for energy savings in large industrial buildings

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ABSTRACT

This paper presents a new method based on a sensor network for designing a lighting control system for an industrial building. An illumination mapping between the work plane and the horizontal plane was derived for sensor placement to generate rules for sensor layout. Online sensor data sampling and a control center database with a real-time update algorithm were applied to lessen the effects of interference and luminous decay. We implemented the method for the lighting system of an industrial building in Xi'an, China. Skylights combined with artificial lighting were designed for daytime lighting. The optimized placement and a scene-control strategy for the artificial lighting system were generated by simulations with DIALux and Autodesk Ecotect Analysis. Daily lighting consumption data for August, 2014, demonstrated that the control system strategy realized lighting energy savings of up to an average of 80% on cloudy days. The design can be used as a reference for new industrial construction or retrofit applications.

1. Introduction

Over the past several years, many researchers have examined the potential energy savings of modern buildings. A significant portion (above 25%) of the total energy consumed in large buildings is used for lighting [1]. Recently, researchers have agreed that a lighting system combining efficient daylight harvesting and artificial lighting can save significant amounts of energy. A daylighting system often exploits light pipes, fiber optics or skylights, in addition to conventional windows, to harvest daylight [2–4]. Considering their initial price and maintenance costs, skylights are best suited for large daylight-lit areas in industrial buildings, whereas the ratio of skylight to roof areas must balance efficient lighting against energy consumption caused by skylight thermal conduction.

Artificial lighting is needed to supplement inadequate daylight, therefore, measurement instruments are essential for automatically controlling lighting. In [5], lux sensors combined with occupancy sensors were designed to detect surroundings, and the two types of sensors were used to decide whether lights should be switched on or off. Indeed, researchers have developed a few control strategies, Francis and Mahmut first proposed sub-period control and daylighting control, which could make effective use of daylight [6]. More recently, constant illuminance control, scene control and movement detection control have been demonstrated to effect savings in lighting consumption [7–9]. However, although a review of the literature finds much research on civil buildings, studies on efficient industrial lighting are far from sufficient, particularly for very large industrial buildings, whose potential for energy savings is high.

A sensor network for data acquisition is an important component of an efficient lighting control system. Although sensors placed closer to objects, may yield more precise data, data from lux sensors installed in the work plane may be unreliable in industrial buildings due to disturbances. High ceilings are also not suitable for sensors in industrial buildings because of the distance to the work plane and the difficulty in providing maintenance. It is generally necessary to perform a study of the layout of sensor nodes and data extraction for a lighting control system.

The objective of our study was to develop a practical way to design and model an efficient lighting system for very large industrial buildings. Relative to the abovementioned literature, the novel aspects of the present study include mapping the illuminance relationship of two horizontal planes in a building space, discussing the rules of sensor layout and using online data acquisition. Dimmable and on-off lamps are usually used to control non-automated

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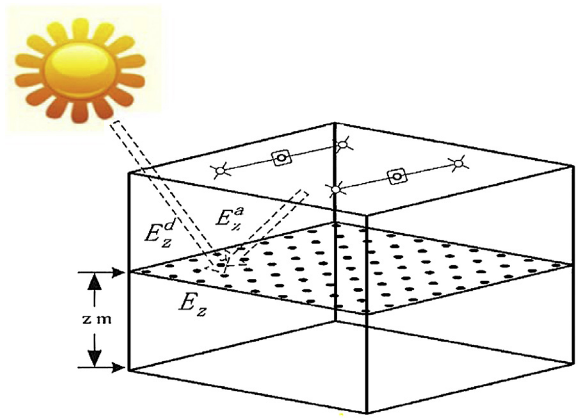

Fig. 1. Representation of point illuminance in the plane.

lighting systems; we therefore introduced a control strategy in this respect. The proposed efficient lighting system is suitable when artificial lighting supplements insufficient natural day light; the control strategy saves as much power as possible while meeting worker requirements. A pre-engineered metal factory located in Xi'an, China, provided a test-bed building for our experiment.

2. Methodology

In a building space, a horizontal plane of height z m is assumed to contain $m \times n$ uniformly distributed points (m rows and n columns). The illuminance at each point is the sum of the daylight and artificial lighting contributions; thus, the illuminance matrix in the z plane shown in Fig. 1 is as follows:

$$\boldsymbol{E_z} = \boldsymbol{E_z^d} + \boldsymbol{E_z^a} \tag{1}$$

$\boldsymbol{E_z^d}$ is the daylight illuminance matrix ($m \times n$) in the plane and $\boldsymbol{E_z^a}$ is the artificial illuminance matrix ($m \times n$) in the plane.

2.1. Daylighting

A lighting environment can be improved by bringing daylight indoors for visual and physical comfort [9]. To make full use of daylight, high visible-light-transmittance glass windows and dormers can be installed if there is no requirement to protect an area from light. The daylight illumination level varies from 1000 lux under a heavily overcast sky to approximately 100,000 lux under direct sunlight. Daylight can not only save electric energy but may also improve production efficiency. According to the definition of the CIE [10]:

$$\text{DF} = \frac{E_i}{E_o} \times 100\% \tag{2}$$

where DF is the daylight factor, E_i is the illumination contributed by daylight at a point indoors in the work plane, and E_o is the simultaneous outdoor illuminance in a horizontal plane from an unobstructed hemisphere of overcast sky. If $\boldsymbol{DF_z}$ is the daylight factor matrix in the z plane, the daylight illuminance matrix ($m \times n$) in the z plane can be written as follows:

$$\boldsymbol{E_z^d} = \boldsymbol{DF_z} E_o \tag{3}$$

$$\boldsymbol{DF_z} = \begin{bmatrix} DF_{z11} & \cdots & DF_{z1n} \\ \vdots & \ddots & \vdots \\ DF_{zm1} & \cdots & DF_{zmn} \end{bmatrix}.$$

Using (3), the relationship between the daylight illuminance matrix $\boldsymbol{E_w^d}$ in the work plane and the daylight illuminance matrix $\boldsymbol{E_z^d}$ in the z plane can be expressed by

$$\boldsymbol{E_w^d} = \boldsymbol{E_z^d} \times \frac{\boldsymbol{DF_w}}{\boldsymbol{DF_z}} = \boldsymbol{E_z^d} \times \boldsymbol{T_{wz}^d} \tag{4}$$

$$\boldsymbol{T_{wz}^d} = \frac{\boldsymbol{DF_w}}{\boldsymbol{DF_z}}$$

$\boldsymbol{DF_w}$ is a daylight factor matrix in the work plane. $\boldsymbol{T_{wz}^d}$ can be defined as a daylight factor transfer matrix between the z plane and the work plane.

2.2. Artificial lighting

In the same manner, let the artificial lighting illuminance matrix in the z plane be $\boldsymbol{E_z^a}$ which is an $m \times n$ matrix as expressed by (5). Each element of $\boldsymbol{E_z^a}$ is the sum of the luminous flux at the corresponding position from all lamps. All lamps in the building can be grouped by type and lighting scene. Suppose there are J groups of lamps in the building and s denotes some point of the matrix $m \times n$ in the z plane. If the luminous flux of each lamp in the jth group is ϕ_j, and the artificial-lighting-distribution factor vector of the jth lamp group at the point s is $\boldsymbol{AF_{sj}}$, then the illuminance at the point s, E_s^a is calculated by (6).

$$\boldsymbol{E_z^a} = \begin{bmatrix} E_{z11}^a & \cdots & E_{z1n}^a \\ \vdots & \ddots & \vdots \\ E_{zm1}^a & \cdots & E_{zmn}^a \end{bmatrix} \tag{5}$$

$$E_s^a = \sum_{j=1}^{J} \phi_j \boldsymbol{AF_{sj1}} \tag{6}$$

Let p denote a point of the $m \times n$ matrix in the work plane. The relationship between the illuminance of the point s and p can be expressed as

$$E_s^a = E_p^a \times \left(\sum_{j=1}^{J} \left\| \phi_j \boldsymbol{AF_{sj}} \right\|_1 \Big/ \sum_{j=1}^{J} \left\| \phi_j \boldsymbol{AF_{pj}} \right\|_1 \right) = E_p^a \times T_{sp}^a$$
$$T_{sp}^a = \sum_{j=1}^{J} \left\| \phi_j \boldsymbol{AF_{sj}} \right\|_1 \Big/ \sum_{j=1}^{J} \left\| \phi_j \boldsymbol{AF_{pj}} \right\|_1 \tag{7}$$

where $\boldsymbol{AF_{pj}}$ is the artificial-lighting-distribution factor vector of the jth lamp group at the point p and T_{sp}^a is the artificial-lighting transfer factor between the points p and s.

2.3. Illuminance fluctuations

Illuminance fluctuations are often taken as input data to the control system and can lead to unstable performance in the lighting control system. A number of factors lead to fluctuations in illuminance at certain points in industrial buildings; for example, light outbursts from the electric arcs create shocks in illuminance, a bridge crane may decrease illuminance when it blocks a skylight or lamp and the voltage fluctuations lead to luminous flux instability, which interferes with lux sensors. Some illuminance fluctuations change occur randomly over a few seconds, some hold constant for longer periods, and some are due to small flickers in the power system.

Fluctuations are inevitable in building environments, particularly in industrial buildings. It is difficult to quantify the effects of fluctuations because lighting systems always involves indeterminate factors that cause these fluctuations. Therefore, a sensor