Energy and Buildings 73 (2014) 105–114

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Daylight-adaptive lighting control using light sensor calibration prior-information

David Caicedo[a,b], Ashish Pandharipande[a,*], Frans M.J. Willems[b]

[a] Philips Research, High Tech Campus, 5656 AE Eindhoven, The Netherlands
[b] Eindhoven University of Technology, The Netherlands

ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form
25 November 2013
Accepted 8 January 2014

Keywords:
Energy-efficient lighting systems
Daylight-adaptive lighting control
Light sensor calibration
Convex optimization

ABSTRACT

We consider a daylight-adaptive lighting control system to adapt dimming levels of artificial light sources with changing daylight, under illumination constraints specified at the horizontal workspace plane of an occupant. We propose a control method for achieving a minimum illuminance at the workspace plane using illuminance measurements at light sensors situated at the ceiling, and additional prior-information from sensor calibration. The proposed method results in a linear programming optimization problem with inequality constraints. Using simulations with photometric data, we compare our sub-optimum solution with the solution where knowledge of the illuminance mapping from the light sensors to workspace illuminance values is available, and with a reference method that is based on satisfying illuminance constraints specified at the light sensors.

1. Introduction

A major part of the total energy consumption in commercial buildings corresponds to artificial lighting [1]. For this reason, several works have focussed on minimizing energy consumption in lighting systems [2–4]. Limited energy consumption may be achieved by providing low illumination levels, but as shown in [5], low illumination levels will also decrease occupant satisfaction, performance and productivity in the office. Further, low illumination can be against the recommended guidelines for illumination levels in offices, e.g. as specified in European norms EN12464-1 [6].

Daylight-adaptive lighting control provides an effective method for energy saving while providing the required illumination levels [2]. This is achieved by adapting the dimming levels of the light sources to produce an artificial illuminance distribution such that when combined with the varying daylight distribution results in a net illuminance distribution that meets the desired illuminance constraints.

The performance of daylight-adaptive lighting control strategies is determined by light sensor measurements. Light sensors should preferably be located in the plane of interest, i.e. the workspace plane [7–11]. In [7–9], centralized lighting control schemes were considered assuming knowledge of light distributions at the workspace plane. In [10], light sensors were placed at the workspace plane, and in [11], a system was considered wherein light sensors were carried by occupants. While it is advantageous to place light sensors directly at the plane where the light distribution is of interest, the light sensor measurements become more sensitive to changes in the environment, e.g. movement of occupants and is thus undesirable.

A different approach, and one widely used in practice, is to place the light sensors at the ceiling plane as in [4,12]. The light sensor measures illuminance within its sensor field of view. In such a system configuration, the light sensor measurements are in a plane different than the plane of interest, i.e. the illuminance measurements are at the ceiling and not at the workspace. Hence, we have limited knowledge about the light distribution at the workspace plane.

In this paper, we consider a lighting system with light sensors co-located at light sources. The light sensor measurements are input to a central controller that determines dimming levels of each light source. The objective of the central controller is to minimize power consumption while maintaining a minimum average illuminance level in various zones in the workspace plane, where zones are a logical partitioning of the workspace plane. Because the light sensors are located in the ceiling plane and not in the workspace plane, a calibration step is required where a relationship between the measured illuminance value at the light sensors in the ceiling plane and the average illuminance value at the workspace plane is obtained. Using the measurements from the calibration step, the central controller translates the illuminance constraints in the workspace plane into illuminance constraints in the ceiling plane. An accurate relationship can be obtained by measuring all the possible illuminance distributions at the workspace plane and

* Corresponding author. Tel.: +31 40 2749741.
E-mail addresses: ashish.p@philips.com, pashish@ieee.org (A. Pandharipande).

0378-7788/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2014.01.022

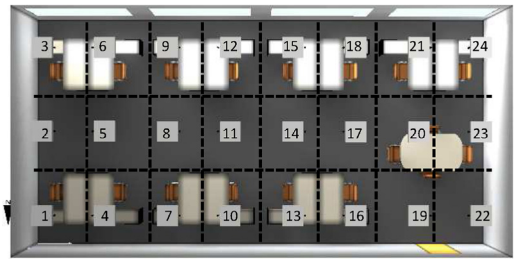

Fig. 1. Top view of office room showing zones.

the corresponding illuminance values at the light sensors. This procedure is however time consuming and so a simplified calibration step is used in practice. Typically, the simplified calibration step is performed during night (dark-room calibration) using an additional light meter [13]. In this step, the light sources are dimmed to a reference value, and the corresponding reference average illuminance values at zones in the workspace plane and reference illuminance values at the light sensors are measured. In some scenarios, using the measurements from the simplified calibration step leads to a lighting system that satisfies the illuminance constraints at the light sensors in the ceiling plane but not the illuminance constraints at the workspace plane.

In our proposed method, we design a central controller that trades-off between power savings and the minimum achievable average illuminance levels at the zones in the workspace plane. The minimum achievable average illuminance level at each zone in the workspace plane for a given dimming vector is formulated as the solution to a constrained optimization problem with a mix of linear and non-convex constraints. We use the calibration prior-information (i.e. reference dimming levels and illuminance measurements) and measured illuminance values at the light sensors to obtain a lower bound, which is linear in the dimming vector, for this constrained optimization problem. We then incorporate the lower bound as an additional constraint in the power minimization problem and solve it, thus resulting in a sub-optimum power saving given the illumination rendering constraints at the workspace plane. The resulting optimization problem is a linear programming problem with inequality constraints. Using photometric data from an indoor open-office scenario, we compare our proposed solution with two other methods: the first one, where knowledge of the illuminance mapping from the light sensors to workspace illuminance values is known; and the second one, where illuminance constraints are specified at the light sensors as in [4].

2. Lighting system description and problem setup

We consider a lighting system in an indoor office as depicted in Fig. 1, with P light sources. Each light source is embedded with a light sensor that has a limited field of view defined by its opening angle. Parallel to the ceiling is the workspace plane where the spatial illuminance distribution is of interest. The workspace plane is assumed to be divided into P logical zones, as shown in Fig. 1. Denote $\boldsymbol{d} = [d_1, d_2, \ldots, d_P]$ to be the dimming vector containing dimming levels, d_n $(0 \le d_n \le 1)$, of the nth light source.

The dimming level of each LED light source is determined by the central controller, under the constraint that the resulting illumination rendered from the lighting system satisfies a minimum target average illuminance level in each zone in the workspace plane. Denote the target average illuminance level at the mth workspace zone, when the mth zone is occupied (respectively, unoccupied), as W_m^o (respectively, W_m^u).

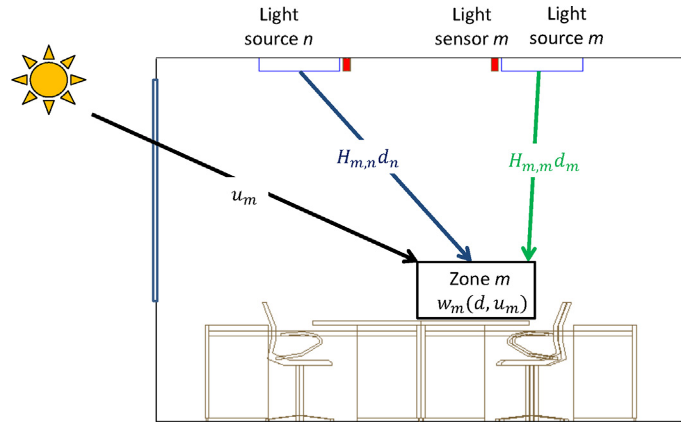

Fig. 2. Average illuminance at zone m at the workspace due to contribution from artificial light and daylight.

2.1. Illuminance at workspace plane

The average net illuminance at the mth zone in the workspace plane, given dimming vector $\boldsymbol{d}$ and under daylight, may be written as

$$w_m(\boldsymbol{d}, u_m) = \sum_{n=1}^{P} H_{m,n} d_n + u_m,$$

where $\sum_{n=1}^{P} H_{m,n} d_n$ and u_m are the illuminance contributions due to lighting system and daylight at the mth zone, respectively, as seen in Fig. 2. Here, $H_{m,n} \ge 0$ is the unknown illuminance contribution to the average in the mth zone when the nth light source is at maximum intensity, with all other light sources turned off. In practice, illuminance values at the workspace place cannot be measured; instead, only illuminance measurements at light sensors are available.

2.2. Illuminance at light sensor

The measured illuminance at a light sensor in the ceiling is the net illuminance due to contributing light sources and daylight reflected from the objects (e.g. furniture) in the office. Denote $E_{m,n}$ as the measured illuminance at the mth light sensor when the nth light source is at maximum intensity, in the absence of daylight. We assume that the illuminance scales linearly with the dimming level. This assumption holds well for practical light sources, e.g. LED light sources.

The net illuminance at the mth sensor at the ceiling, given that the lighting system is at dimming vector $\boldsymbol{d}$ and under daylight, can then be written as

$$l_m(\boldsymbol{d}, s_m) = \sum_{n=1}^{P} E_{m,n} d_n + s_m, \quad (1)$$

where $\sum_{n=1}^{P} E_{m,n} d_n$ is the illuminance due to the lighting system and s_m is the illuminance due to daylight measured at the mth sensor, as seen in Figs. 3 and 4, respectively. In practice, the mappings $E_{m,n}$ may be computed a priori in a calibration phase by turning on the light sources to the maximum intensity one at a time and measuring illuminance values at the light sensors.

Further, we can relate the average illuminance values at the workspace plane and illuminance values at light sensors by

$$\sum_{n} E_{m,n} d_n = \sum_{n} \sum_{p} G_{m,p}^{(n)} H_{p,n} d_n, \quad (2)$$