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Personal lighting control with occupancy and daylight adaptation

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ABSTRACT

Personal control with occupancy and daylight adaptation is considered in a lighting system with multiple luminaires. Each luminaire is equipped with a co-located occupancy sensor and light sensor that respectively provide local occupancy and illumination information to a central controller. Users may also provide control inputs to indicate a desired illuminance value. Using sensor feedback and user input, the central controller determines dimming values of the luminaires using an optimization framework. The cost function consists of a weighted sum of illumination errors at light sensors and the power consumption of the system. The optimum dimming values are determined with the constraints that the illuminance value at the light sensors are above the reference set-point at the light sensors and the dimming levels are within physical allowable limits. Different approaches to determine the set-points at light sensors associated with multiple user illumination requests are considered. The performance of the proposed constrained optimization problem is compared with a reference stand-alone controller under different simulation scenarios in an open-plan office lighting system.

1. Introduction

The major portion of electrical energy consumption in commercial buildings is due to lighting for office spaces [1]. Energy consumption may be reduced by using appropriate lighting control techniques. Thus the control of artificial lighting has recently received significant attention, in particular by adapting to occupancy and daylight changes over time and space [2–11]. The adoption of light emitting diode (LED) luminaires has made such control easy since it is possible to accurately dim each luminaire individually taking into account local presence and light sensing inputs. While saving energy is an important objective, controller design must also take personal illumination needs of users into account. In fact, studies have shown that users may require differing levels of illumination and a lighting system that caters to these needs can enhance user satisfaction and productivity [12–14].

In this work, we consider a lighting system with multiple luminaires and a central controller. Each luminaire has a co-located occupancy sensor and a light sensor. These sensors respectively provide binary occupancy and the net illuminance level within their field-of-view. Additionally, users may request for a desired illuminance levels in their zone. The sensing values and user requests are sent to a central controller, where a designed control law is used. The dimming levels are evaluated by the controller and sent back to the corresponding luminaires. The control law has to be designed such that the total artificial light output contribution, in combination with daylight contribution, results in net illuminance above desired levels at the workspace plane.

The illuminance targets at the workspace plane are specified in terms of sensor set-points at corresponding light sensors co-located at the ceiling luminaires. These set points are determined in a night-time calibration step. In the absence of daylight, the luminaires are turned to maximum intensity and the average workspace illuminance value along with the light sensor measurements is stored. The light sensor set-points corresponding to a specific desired average illuminance are then obtained by suitable linear scaling. In the calibration step, the illumination gain between luminaire-light sensor pairs are also obtained. This is done by turning on each luminaire at its maximum intensity, with no external light contribution, and measuring the light sensor values.

Two lighting control scenarios are considered in this paper. In the first scenario, lighting control is based solely on pre-specified illumination targets in occupied and unoccupied zones and control feedback is from the occupancy and light sensors. In the second scenario, lighting control is based additionally on user control requests. In this scenario, we consider different approaches to specify the set-points of light sensors that are associated with multiple user requests.

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We pose the lighting control problem using an optimization framework. The optimum dimming values are obtained by minimizing a cost function that is a weighted sum of a component related to the illumination errors at the light sensors and another component related to the power consumption of the lighting system. The optimization is under the constraints that the illuminance value attained at the light sensors is no smaller than the reference set-points and that the dimming levels of the luminaires take values within physical limits. This constrained multi-variable minimization problem is then solved using convex optimization techniques. We evaluate the performance of the proposed control algorithm with simulations on an illustrative open-plan office. Using a stand-alone controller [11] as benchmark, we show that the proposed approach provides better transient behavior and also has better performance in terms of under-illuminance. We use overshoot and settling time [15] to characterize the transient behavior of the control system. The amount of illumination is used as a performance metric as it is related to the comfort preference of users [16–18]. The reader is referred to [17] for an in-depth literature survey of user comfort aspects to be considered in daylit office buildings.

Various optimization based frameworks have been proposed in literature for daylight and occupancy adaptation [2–4,19,20]. In [19] a centralized lighting control system was considered resulting in a linear programming problem. This system was then extended in [20] to take into account spatio-temporal daylight variations. In these works, knowledge of the light distribution at the workspace plane was assumed; the performance reported as such can be seen as theoretical performance limits. Two networked lighting systems were taken into account in [4,5] by considering the light sensors at work desks. In particular in [5] the authors proposed a distributed lighting system equipped with a controller which was able to control luminaires in a neighborhood using infra-red communication. It is common practice to install the light sensors at the ceiling [8,11,21,22]. In this case, since light measurements are on a plane different from the one where the spatial illumination rendering is of interest, a calibration step is required to map the measurements across the ceiling and workspace planes.

The remainder of the paper is organized as follows. In Section 2, we present an analytical model of the lighting system under consideration. In Section 3, we first explain how the light sensor set-points are chosen. The proposed constrained optimization method is then described. The performance of the proposed controller is evaluated and compared with the stand-alone controller using an open-plan office model and results are discussed in Section 4. Finally in Section 5 conclusions are drawn.

2. System model

A lighting control system in an illustrative open-plan office area is considered as shown in Fig. 1.

The lighting system has M ceiling-based luminaires and a central controller. Each luminaire has an occupancy sensor and a light sensor. The occupancy sensor detects whether there is local unoccupancy or occupancy within its field-of-view, and then provides a binary value, 0 or 1 respectively. The illuminance measurement at the light sensor corresponds to the net amount of light (daylight contribution and artificial light from the luminaires) reflected back within its field-of-view from various objects. These sensor measurements are sent periodically to the central controller. Additionally, users may request desired illuminance values over his/her occupied zone and such information is available to the controller. At the controller, the dimming levels are computed based on an optimization framework and then communicated back to the luminaires. The sensor feedback period is chosen such that the controller reacts with sufficient speed to daylight changes, while not overloading the communication bandwidth; practical choice for the period is in the order of seconds. In this work we shall assume high bandwidth communication; communication is thus assumed to be reliable and message losses and delays are ignored.

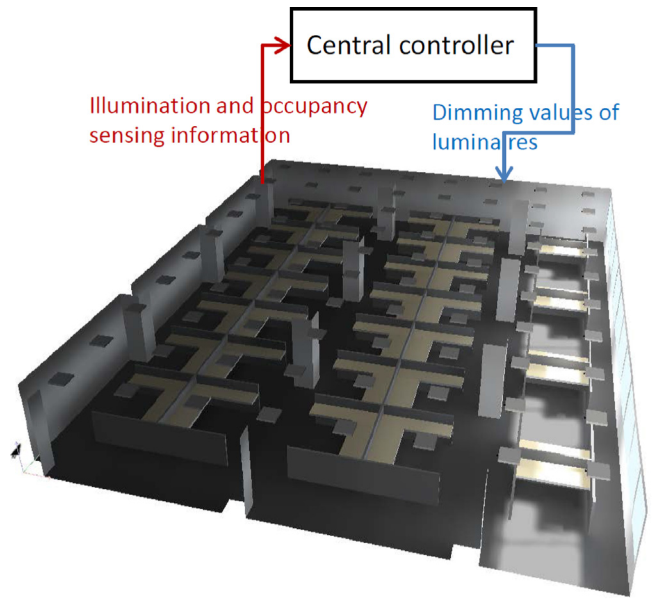

Fig. 1. Lighting control system with multiple luminaires and co-located sensors in communication with a central controller.

Let the luminaires be dimmed using pulse width modulation (PWM). Let the mth luminaire be dimmed linearly with duty cycle $u_m(k)$ at time k, where $0 \leq u_m(k) \leq 1$. The linearity assumption holds well for LED luminaires [8]. Under this assumption, the power consumption of the luminaires may be approximated to be directly proportional to the dimming level. In this way, minimizing the power consumption of the entire system is equivalent to minimizing the 1-norm of the dimming vector $\mathbf{u}(k) = [u_1(k), u_2(k), \ldots, u_M(k)]^T$,

$$||\mathbf{u}(k)||_1 = \sum_{m=1}^{M} |u_m(k)| = \sum_{m=1}^{M} u_m(k). \quad (1)$$

The illuminance value at light sensor m can be modeled as a linear combination of the artificial illumination and the daylight contribution [8,11],

$$y_m(k+1) = \sum_{n=1}^{M} G_{m,n} u_n(k) + d_m(k+1), \qquad m = 1, \ldots, M \quad (2)$$

where $G_{m,n}$ is the illuminance gain, which is the illuminance value at the mth light sensor when the nth luminaire is set at its maximum intensity, while all other luminaires are off and there is no other source of light; $d_m(k)$ is the illuminance contribution at the mth light sensor due to daylight at time k.

In matrix form, (2) may be rewritten as

$$\mathbf{y}(k+1) = G\mathbf{u}(k) + \mathbf{d}(k+1), \quad (3)$$

where $\mathbf{y}(k) = [y_1(k), y_2(k), \ldots, y_M(k)]^T$ is an $M \times 1$ vector containing the light sensor measurements, $\mathbf{d}(k) = [d_1(k), d_2(k), \ldots, d_M(k)]^T$ is an $M \times 1$ vector with the daylight contribution at the light sensors, and G is an $M \times M$ matrix containing the illumination gains.

The illumination achieved by lighting control over the horizontal workspace plane is typically of interest in office lighting applications. We consider this plane to be divided into N logical zones, where a zone may correspond to the working area of a user. A