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Lighting control with distributed wireless sensing and actuation for daylight and occupancy adaptation

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ABSTRACT

Daylight and occupancy adaptive control is considered for a wireless mesh networked lighting system with multiple sensor-equipped luminaires and a central controller. Each luminaire in the system has a co-located light sensor, occupancy sensor and a wireless radio. The light and occupancy sensors respectively determine net average illuminance and occupant presence within their sensor fields-of-view and report these values on the wireless medium to a central controller. Based on the sensing information, the central controller computes dimming levels of the luminaires, so as to satisfy a desired illumination objective, and transmits them back to the corresponding luminaires. The illumination objective is to provide a minimum average illuminance value over occupied and unoccupied zones at the workspace, specified in turn by occupancy-based set-points at the corresponding light sensors. To achieve the illumination objective, stand-alone proportional–integral (PI) control law at the central controller is considered. In this paper, the performance of such a wireless lighting control system is studied. To make the performance of the lighting system robust to wireless impairments, transmission redundancy and enhancements in the controller are considered. The performance of the proposed system is evaluated for an example open-plan office lighting model under different daylight and occupancy scenarios and a ZigBee wireless network.

1. Introduction

Office lighting in commercial buildings is known to constitute a major portion of the electrical energy consumption [1]. Control of artificial lighting to save energy has thus received significant attention, in particular by adapting to daylight and occupancy [2–5]. The advent of light emitting diode (LED) based luminaires has made it possible to control artificial lighting easily and flexibly. Thus it is possible to adapt LED based luminaires to daylight and occupancy at a fairly granular spatio-temporal level. In particular, systems with sensor-equipped luminaires offer high sensing granularity and have been considered recently [3,6,7,10].

In this paper, we consider a wireless mesh networked lighting system with multiple sensor-equipped luminaires and a central controller. The topology of a wireless lighting control system in an open office is illustrated in Fig. 1. In the system, each luminaire has a co-located light sensor and occupancy sensor. The light sensor determines the average illuminance from daylight and artificial light incident within its field-of-view. The occupancy sensor results in a binary value – one, under occupant presence within the field-of-view and zero otherwise. The sensor results are transmitted to the central controller, and fed to a respective PI control law. The output of the control law is a dimming level for the corresponding luminaire and this value is transmitted to the luminaire. In such a lighting control system architecture, the control intelligence entirely resides at the central controller and the wireless sensors and luminaires themselves only need to adhere to the chosen wireless protocol. This allows greater flexibility in system specification in comparison to a distributed lighting control architecture [3,8], where the control intelligence resides at the luminaires.

The dimming levels of each luminaire are to be determined by corresponding PI control laws such that the total artificial light output contribution, in combination with daylight contribution, results in net illuminance above desired levels at the workspace plane. Let W_o and W_u denote the respective target average illuminance values in an occupied and unoccupied zone at the workspace; a zone being a logical partitioning, for instance that defines a region around work desks, of the physical horizontal workspace plane. As an example, European norms for office lighting recommend minimum average illuminance values of $W_o = 500$ lux and $W_u = 300$ lux [9]. The target average illuminance values at the workspace plane are specified in terms of sensor set-points at corresponding light sensors. These

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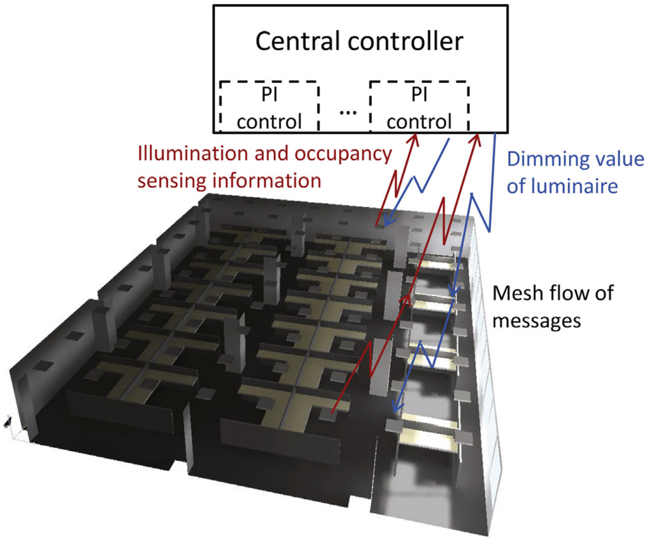

Fig. 1. Topology of a wireless mesh networked lighting system with multiple sensor-equipped luminaires and central controller.

set-points are determined in a night-time calibration step. In the absence of daylight, the luminaires are dimmed to a level so that the desired illuminance, say W_o, is achieved and the corresponding light sensor measurements $\{r_{o,m}\}$ are stored as the associated set-points. Let $r_{o,m}$ and $r_{u,m}$ be respectively the set-points of the mth light sensor corresponding to occupancy and non-occupancy. Then the control objective is to at least achieve this set-point, while limiting overshoot and oscillations in dimming (i.e. system should achieve steady-state), and achieving power savings. Overshoot is the peak value compared to the final steady-state value.

A wireless lighting system is easier to deploy in comparison to a wired system, and is attractive for retrofitting new lighting controls with minimal disruption. Wireless systems however suffer from unreliable communications leading to packet losses and delays. We consider the effect of wireless channel impairments on the performance of the considered lighting control system. In particular, our goal is to design a wireless lighting control system, under the topology shown in Fig. 1, that results in an illumination performance similar to the wired counterpart. Performance indicators such as settling time and overshoot commonly used in steady-state performance analysis of control systems [10] are employed. This then ensures lighting experience to a user agnostic of the communication interface.

A centralized lighting control system was considered in [11] for occupancy adaptive lighting resulting in a linear optimization problem. This system was extended in [4] to take into account spatio-temporal daylight variations. Knowledge of light distribution at the workspace plane was assumed in both formulations. Distributed optimization algorithms for lighting control with daylight and occupancy adaptation were proposed in [3,6,12], under networking and information exchange constraints. Under different system settings, and wherein users carried light sensors, linear programming and sequential quadratic programming approaches were proposed for centralized lighting control [13,14]. A wireless networked lighting system with light sensors at work desks was considered in [15,16]. In [17], a distributed lighting system was proposed with light sensors at desks, and equipped with a controller, which control luminaires in a neighborhood using infra-red communication. Measurements of light sensors in a desk-placed or portable configuration can however be sensitive to environmental changes such as occupant movements and shadowing of objects, thus affecting illumination performance of the lighting system. It is thus common practice to use ceiling-mounted sensor configurations [3,7,18,19]. Stand-alone as well as networked controllers for distributed lighting systems were considered in [7], under the assumption of perfect communication channel. Herein, a PI control law with offset was considered. The positive offset in the control law was introduced to deal with the problem of under-illumination that occurs due to different contributions of daylight over the workspace and light sensors over time. This observation was made early in [19,20], for a singe light sensor-driven lighting system.

2. System model

2.1. Analytical model

Consider a lighting system with M ceiling-based luminaires. Each luminaire has a co-located light sensor and occupancy sensor, and that can communicate with a central controller using a wireless radio. Let the luminaire be dimmed using pulse width modulation (PWM). Let the nth luminaire be dimmed linearly with duty cycle $u_n(k)$ at time instant k, where $0 \le u_n(k) \le 1$.

Each light sensor samples at a sampling period T_s. Given that sensing is distributed, the sampling is not synchronous across sensors. The illuminance value at light sensor m can be written as [7]

$$y_m(kT_s+\tau_m) = G_{m,m}u_m((k-1)T_s+\tau_m) + d_m(kT_s+\tau_m) + \sum_{n \neq m} G_{m,n}u_n(kT_s+\tau_n) \qquad (1)$$

where τ_m is a constant random delay, $-\frac{T_s}{2} \le \tau_m \le \frac{T_s}{2}$, for each instance of the controller, and $k \in \mathbb{N}$. The constant delay between controllers reflects the asynchronous nature of the system. The last term represents the coupling among luminaires/sensors. In (1), $G_{m,n}$ is the illuminance value at the mth light sensor when the nth luminaire is dimmed at its maximum, 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 in lux due to daylight at time k. Denote G to be the $M \times M$ matrix with (m, n)th element $G_{m,n}$. The elements $G_{m,n}$ may be obtained in a night-time calibration step and are known.

Consider now that the light sensors are ordered by the order of their execution. With this ordering, let $\hat{G}$ be the sorted matrix representing the relation between the luminaire dimming level and the sensor measurement, in the absence of daylight. The first row of $\hat{G}$ thus represents the illuminance contributed from the luminaires to the first sensor which is sampled in the system. In matrix form, the model is written as

$$\mathbf{y}(k) = (\hat{G}_d + \hat{G}_u)\mathbf{u}(k-1) + \hat{G}_l\mathbf{u}(k) + \mathbf{d}(k), \qquad (2)$$

where $\mathbf{y}(k)$ and $\mathbf{d}(k)$ are $M \times 1$ vectors containing components $y_m(k)$ and $d_m(k)$ respectively. $\hat{G}_d$ is the diagonal part of $\hat{G}$, $\hat{G}_u$ the strictly upper triangular part of $\hat{G}$ and $\hat{G}_l$ the strictly lower triangular part of $\hat{G}$, so that

$$\hat{G} = \hat{G}_d + \hat{G}_u + \hat{G}_l. \qquad (3)$$

We consider stand-alone single-input, single-output (SISO) control laws. In comparison to multi-variable control laws that can potentially offer better performance, SISO control laws offer simplicity of implementation [21,22]. In Fig. 2, one such SISO PI controller is illustrated. The controller calculates the dimming level of the luminaire so as to achieve the light sensor reference value $\left\{r_{o,m}\right\}$ in case of local occupancy, or $\left\{r_{u,m}\right\}$ in case of local unoccupancy and global occupancy. A zero order hold (ZOH) filter is used at the luminaire to obtain the continuous dimming level, $u_m(t)$.