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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.

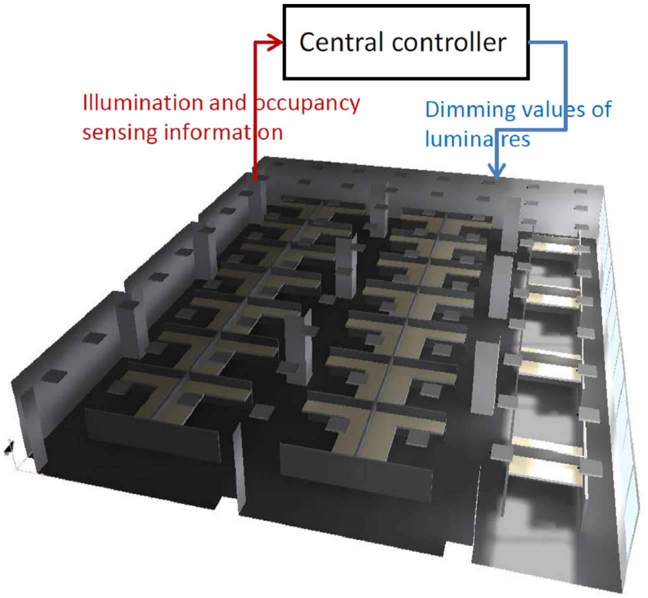

Fig. 1. Lighting control system with multiple luminaires and co-located sensors in communication with a central controller.

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 $\mathbf{u}(k) = [u_1(k), u_2(k), \ldots, u_M(k)]^T$,

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

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

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

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

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

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 night-time calibration step is used to translate desired illuminance values over a zone to reference set-points at the ceiling located light sensors. We consider two lighting control scenarios. In the first scenario, labeled hereon as “sensor-driven lighting control” scenario, lighting control is achieved based only on sensor feedback. Thus the target illuminance over zones is translated into light sensor set-points based on local occupancy and target illuminance over a zone. For instance, the target may be $W_o = 500$ lx and $W_u = 300$ lx over a locally occupied and locally unoccupied/area occupied zone respectively, with the specific values chosen following European norms for office lighting [23]. In the second scenario, labeled hereon as “sensor-driven personal lighting control” scenario, lighting control is achieved based only on sensor feedback and user personal control inputs. A user may specify desired illuminance in his/her occupied zone and light sensor reference set-points are set accordingly. The controller then employs an optimization framework to determine the optimum dimming levels of the luminaires.

3. Lighting control

We consider a lighting controller whose objective is to minimize a weighted sum of squares of the illuminance errors at light sensors and square of the power consumption, while satisfying the following constraints: (i) the illuminance value at each light sensor is above the reference set-point, and (ii) the dimming levels of the luminaires can only take values within physical limits.

We first consider how the reference set-points at light sensors are specified.

3.1. Reference set-points at light sensors

In the “sensor-driven lighting control” scenario, the set-points are computed using the measurements stored in the night-time calibration step by setting all the luminaires to maximum intensity, with no external light contribution. Let r_m denote the value at light sensor m and W denote the average illuminance value over the workspace plane. Then the light sensor set-point for locally occupied and locally unoccupied/area occupied states respectively denoted by $r_{o,m}$ and $r_{u,m}$ are given by

$$r_{o,m} = \frac{W_o \cdot r_m}{W}, \qquad r_{u,m} = \frac{W_u \cdot r_m}{W}, \tag{4}$$

where $W_o < W$ and $W_u < W$ are the corresponding desired illuminance levels.

In the “sensor-driven personal lighting control” scenario, there may be light sensors associated to multiple zones. As such, there are multiple approaches to specify the reference set-points of these light sensors. Consider light sensor m that is associated with neighboring zones indexed by set $\mathcal{N} = \{n_1, \ldots, n_K\}$. Consider $n_k \in \mathcal{N}$ and let W_{n_k} denote the illuminance value desired by a user (this value can also be the default level W_o or W_u depending on the occupancy state over the zone) in zone n_k. We consider three approaches to specify the reference set-points at the shared light sensors.

(i) Minimum approach: the reference set-points at a shared light sensor m is specified as,

$$r_m^{(\min)} = \frac{\min_{n_k \in \mathcal{N}} W_{n_k} \cdot r_m}{W}. \tag{5}$$

In this case, the illuminance of the least demanding user is used to specify the set-points of the shared light sensors. This choice is expected thus to have lower power consumption.

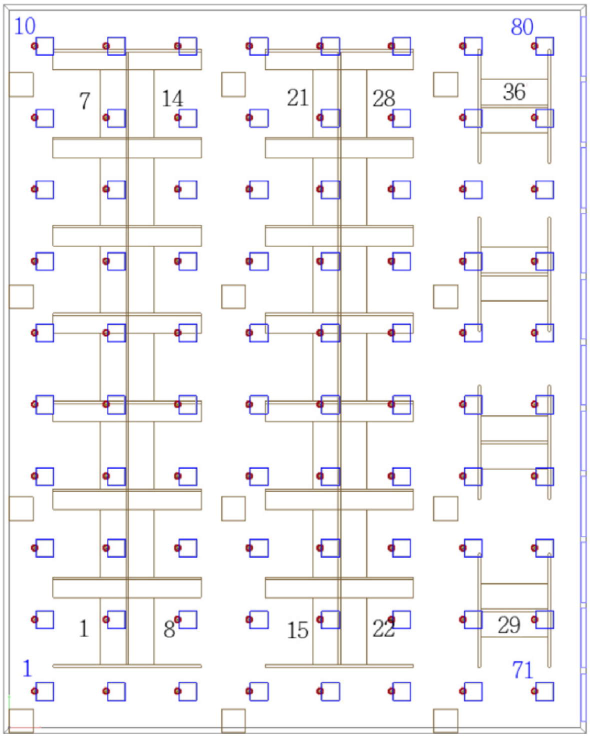

Fig. 2. Open-plan office lighting system with 80 luminaires (blue squares) with co-located light/occupancy sensors (red circles) and 36 zones. The windows are on the right side of the room. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

(ii) Maximum approach: the reference set-points at a shared light sensor m is specified as,

$$r_m^{(\max)} = \frac{\max_{n_k \in \mathcal{N}} W_{n_k} \cdot r_m}{W}. \tag{6}$$

In this case, the illuminance of the most demanding user is used to specify the set-points of the shared light sensors, and this choice is expected to satisfy illuminance requirements of each user, if a solution is feasible.

(iii) Average approach: the reference set-points at the shared light sensors are selected as an average value as follows,

$$r_m^{(\text{ave})} = \frac{1}{K} \cdot \frac{\sum_{n_k \in \mathcal{N}} W_{n_k} \cdot r_m}{W}. \tag{7}$$

This choice should provide a trade-off between limiting the power consumption and satisfying illumination desired by users.

3.2. Lighting control algorithm using constrained optimization

In the optimization framework, we consider a cost function given by

$$f(\mathbf{u}(k)) = \left\{ \lambda ||\mathbf{y}(k+1) - \mathbf{r}||_2^2 + (1-\lambda)||\mathbf{u}(k)||_1^2 \right\}, \tag{8}$$

where $\mathbf{r} = [r_1, r_2, \ldots, r_M]^T$ is the vector containing the reference set-points. The first term captures the norm of the error at light sensors; the term $||\mathbf{y}(k+1) - \mathbf{r}||_2^2$ is the square of the 2-norm of the difference between the vector with the light sensor values and the vector with the reference set-points. The second term $||\mathbf{u}(k)||_1^2$ is the square of the power consumption (1). In (8), $0 \le \lambda \le 1$ is a design parameter that balances the deviations of achieved illuminance at the light sensors from the reference set-points and with the power

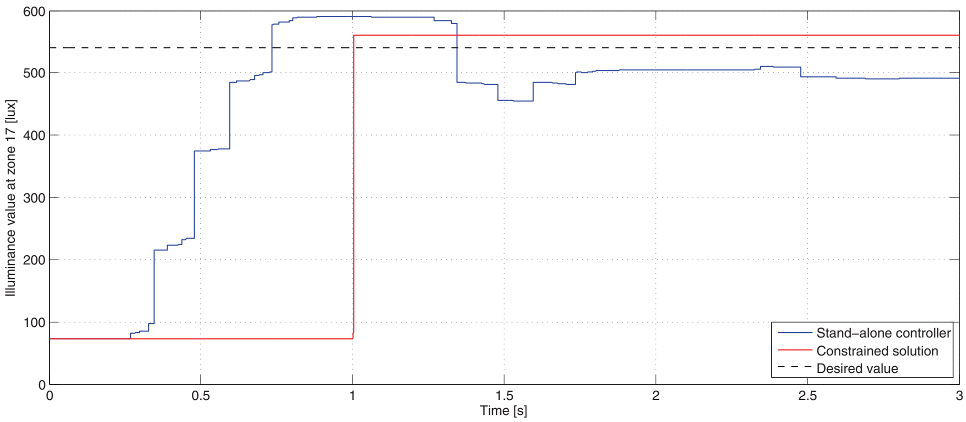

Fig. 3. Transient behavior of the controllers.

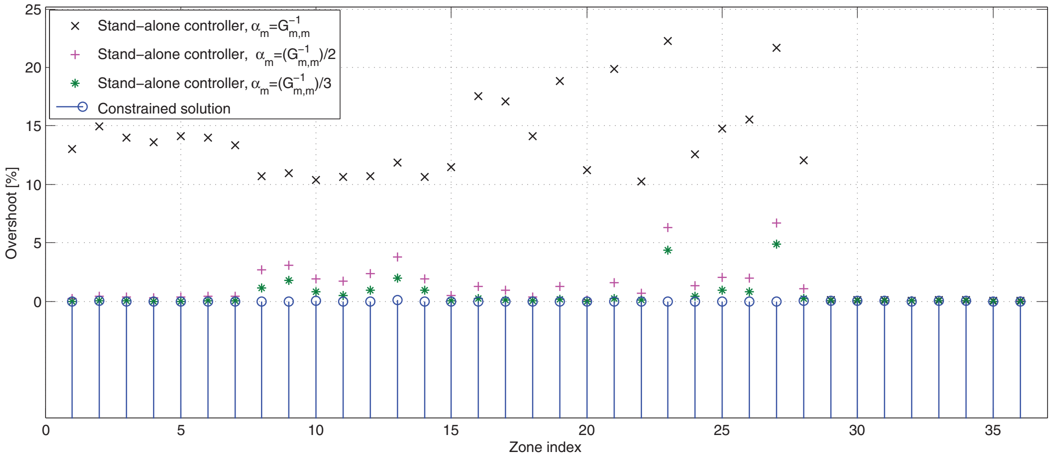

Fig. 4. Average overshoot of illumination at each zone for different values of the gain α_m (1000 simulations for each case).

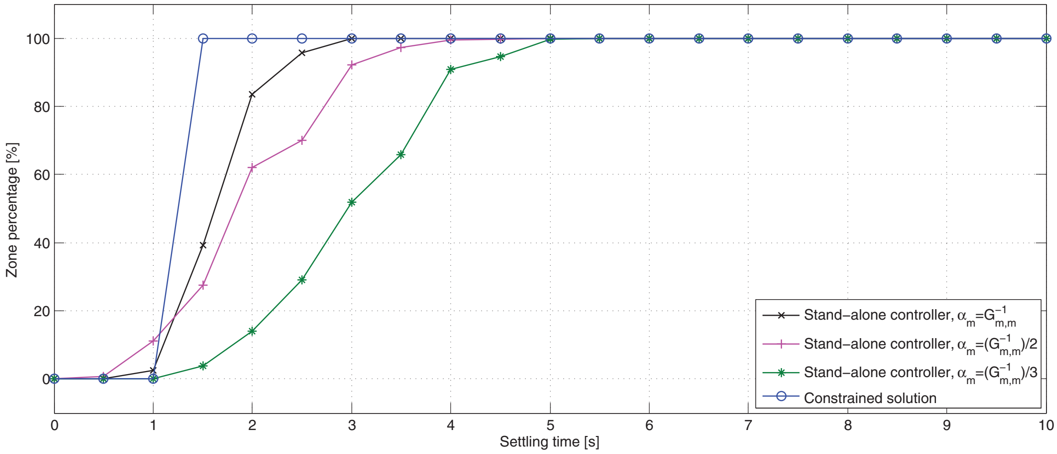

Fig. 5. Settling time for different values of the gain α_m (1000 simulations for each case).

consumption. The optimization is done under the following constraints

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

$$\mathbf{0} \leq \mathbf{u}(k) \leq \mathbf{1},$$

where the above inequalities hold component-wise, **0** and **1** are vectors with each component 0 and 1 respectively. At iteration k, the dimming vector $\mathbf{u}(k)$ is updated by

$$\mathbf{u}(k) = \begin{cases} \mathbf{u}^{\star}(k), & \text{if } \|\mathbf{u}(k-1) - \mathbf{u}^{\star}(k)\|_2 \geq \epsilon, \\ \mathbf{u}(k-1), & \text{otherwise,} \end{cases}$$

Table 1
Percentage of zones that reached the steady state value in 2 s (1000 simulations for each case).

Controller	Zone percentage
Constrained solution	100%
Stand-alone controller, $\alpha_m = G_{m,m}^{-1}$	82%
Stand-alone controller, $\alpha_m = G_{m,m}^{-1}/2$	63%
Stand-alone controller, $\alpha_m = G_{m,m}^{-1}/3$	16%

where $\epsilon \geq 0$ is a deadband and $\mathbf{u}^{\star}(k)$ is the optimum dimming vector obtained by solving the following optimization problem at iteration k:

$$\mathbf{u}^{\star}(k) = \min_{\mathbf{u}(k)} \{\lambda ||G\mathbf{u}(k) + \mathbf{d}(k+1) - \mathbf{r}||_2^2 + (1-\lambda)||\mathbf{u}(k)||_1^2\}, \tag{9}$$

$$G\mathbf{u}(k) + \mathbf{d}(k+1) \geq \mathbf{r}, \tag{10}$$

$$\mathbf{0} \leq \mathbf{u}(k) \leq \mathbf{1}. \tag{11}$$

Note that the above optimization problem always has a feasible solution for the "sensor-driven lighting control" scenario, given that $\mathbf{d}(k) \geq 0$ and $G\mathbf{1} \geq \mathbf{r}$ holds due to the calibration step. Note that the illumination error is captured in both the first term of the cost function as well as in the first constraint. This ensures that the attained light sensor values at the optimum solution will be close to the set-points, as opposed to an optimizing solution where this term is not taken into account in the cost function ($\lambda = 0$ case).

In the optimization framework, the daylight term in (9) and in (10) is not explicitly known. However since temporal daylight variations are usually slow, we may assume that daylight changes slowly within the sensor sampling period. The daylight value is thus estimated from the previous iteration as

$$\mathbf{d}(k+1) \approx \mathbf{d}(k) = \mathbf{y}(k) - G\mathbf{u}(k-1), \tag{12}$$

and used in the optimization problem.

Note that the cost function in (9) is quadratic in the dimming levels and the inequality constraints are linear in the dimming levels. Such optimization problems can be solved to determine the globally optimum dimming vector using efficient quadratic programming algorithms like the interior-point and variants [24].

3.3. *Stand-alone controller*

The stand-alone controller proposed in [11] is used as a benchmark. In this work the authors address the multivariate control problem designing multiple stand-alone controllers where each controller evaluates its dimming level independent of each other. This means that the mth controller seeks to achieve the reference set-point $r_{o,m}$ if the mth occupancy sensors determines local occupancy or the set-point $r_{u,m}$ if the mth occupancy sensors determines local unoccupancy/area occupancy. The dimming level for the mth luminaire at time instant k is given by the following law:

$$u_m(k) = \alpha_m e_m(k) + \beta_m u_m(k-1). \tag{13}$$

In (13), $\alpha_m > 0$ and $\beta_m > 0$ are controller gains respectively and $e_m(k) = r_m(k) - y_m(k)$ is the error at the light sensor m at time instant

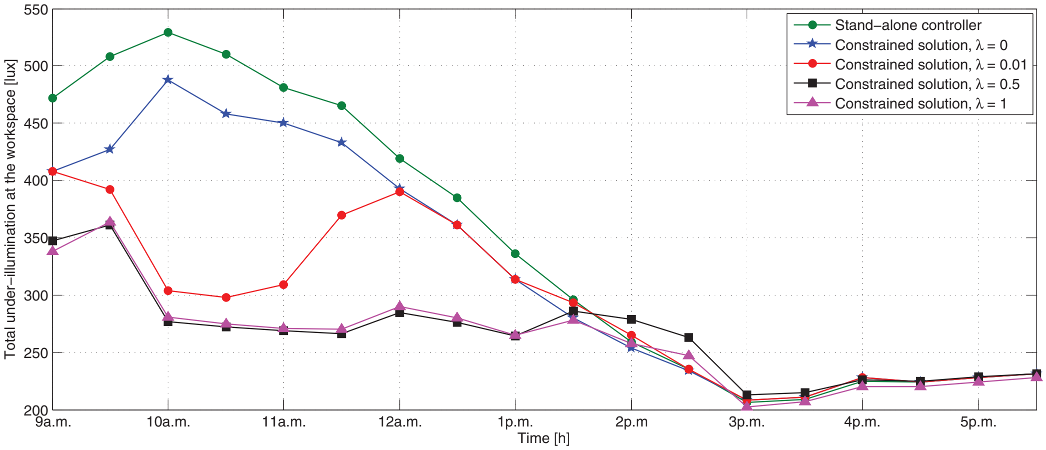

Fig. 6. Comparison of total under-illumination over all zones.

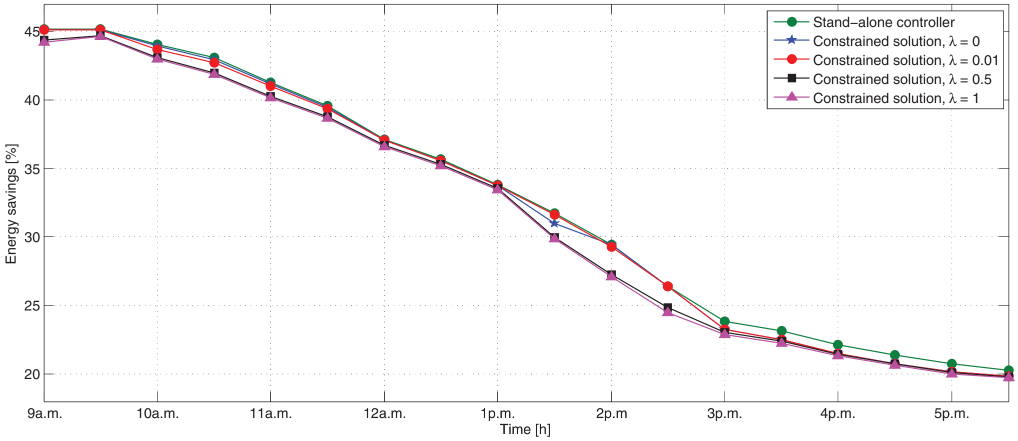

Fig. 7. Comparison of energy savings.

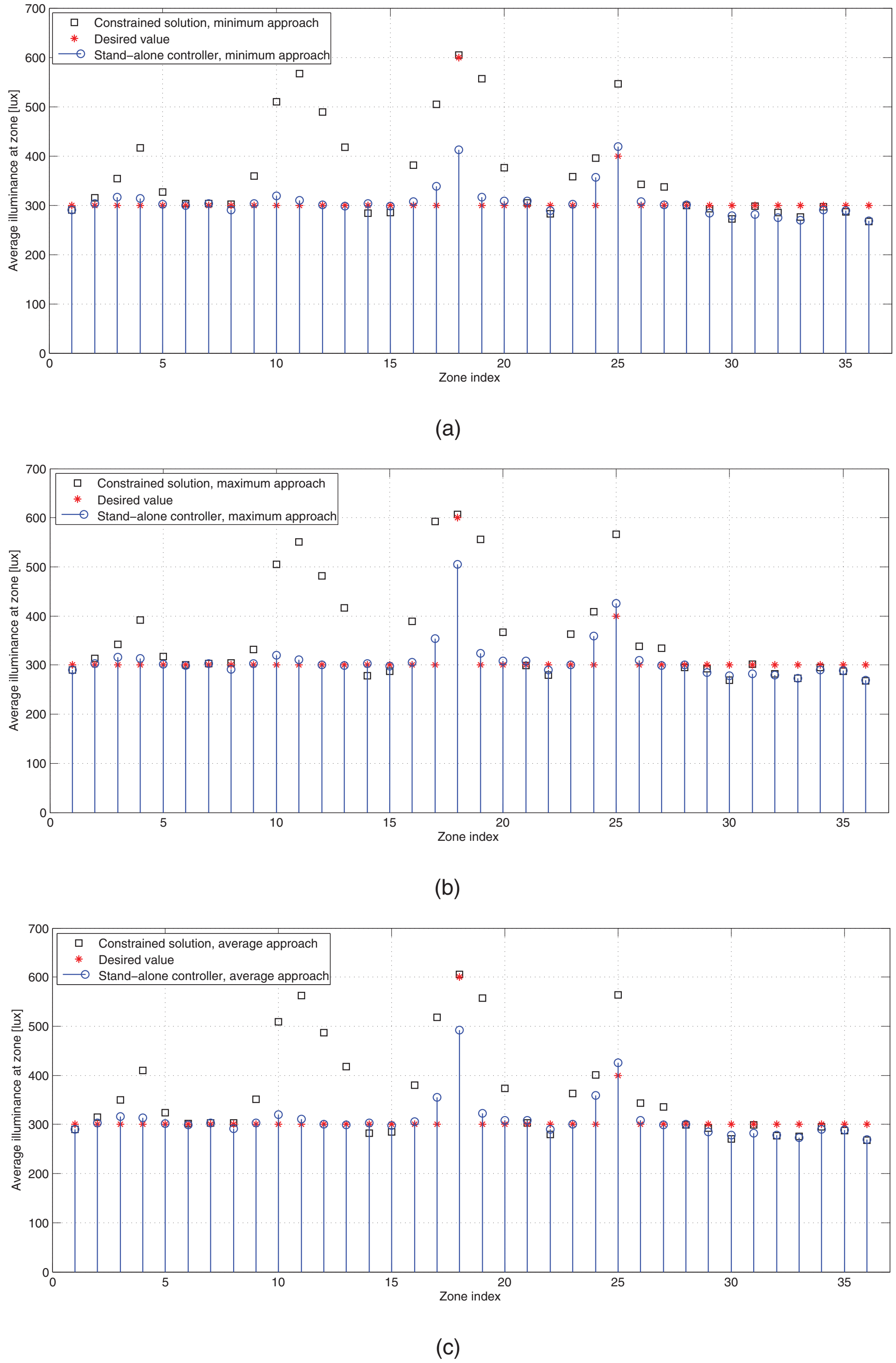

Fig. 8. Steady-state value of the illuminance at zones with the (a) minimum approach, (b) maximum approach, and (c) average approach.

k. The gains α_m and β_m are chosen in order to have a stable closed-loop system.

4. Simulation results

In this section we show simulation results to evaluate and compare the performance of the proposed control algorithm with the reference stand-alone controller, under the two considered control scenarios. For comparison, we exclude the effect of deadband by choosing $\epsilon = 0$.

4.1. Office lighting model and parameter description

The open-plan office model considered in [11] and implemented in DIALux [25] is used for simulations. The office has length 24 m and width 19 m with height of the ceiling of 2.6 m. There are $M = 80$ luminaires and sensors organized in a grid of 10 by 8, with $N = 36$

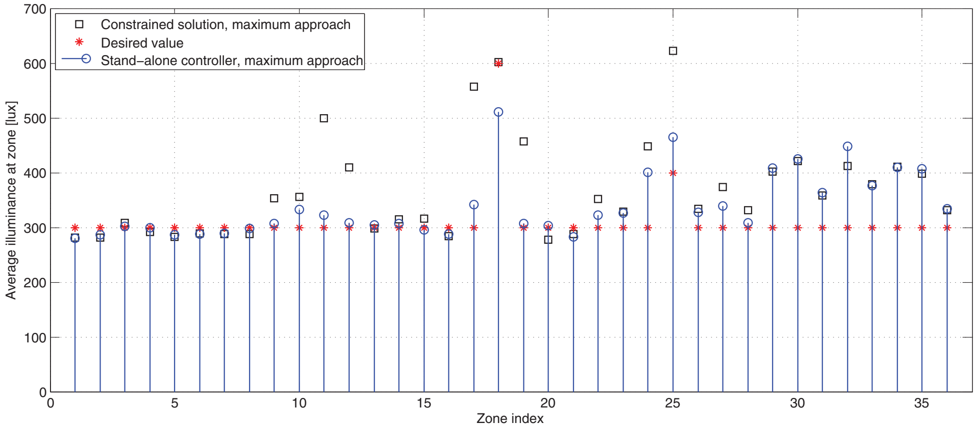

Fig. 9. Steady-state value of the illuminance at zones with the maximum approach, daylight at 5 pm.

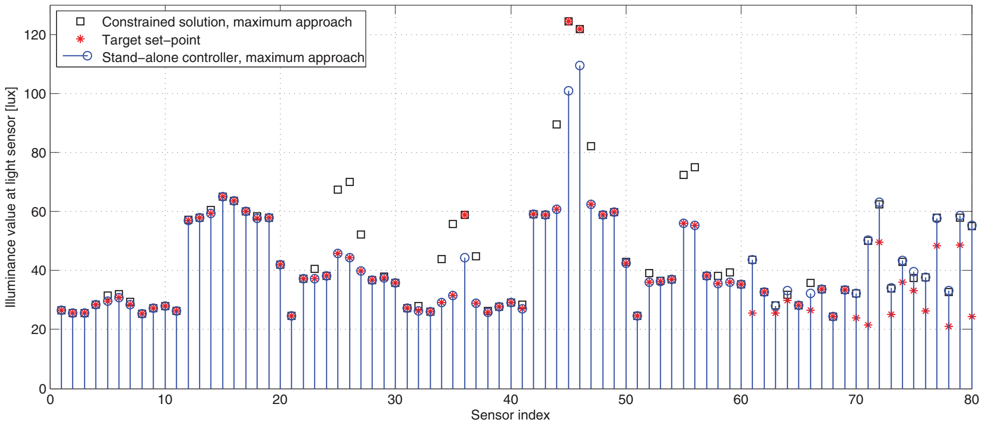

Fig. 10. Steady-state value of illuminance at light sensors with the maximum approach, daylight at 5 pm.

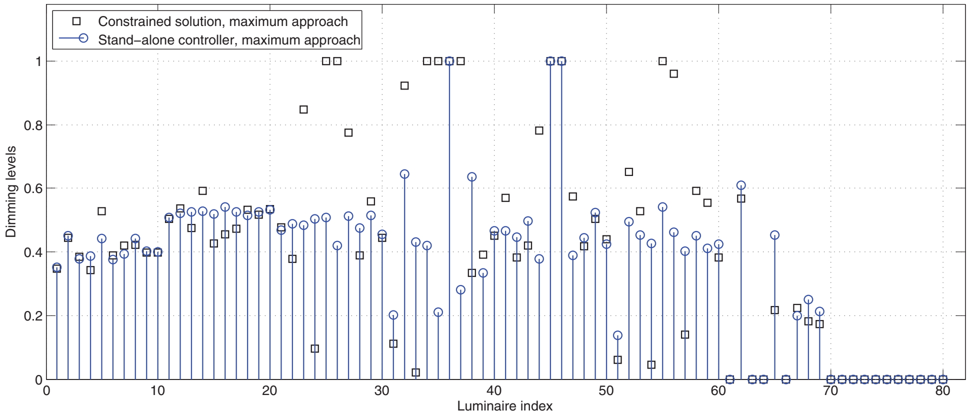

Fig. 11. Steady-state value of dimming levels with the maximum approach, daylight at 5 pm.

zones as depicted in Fig. 2. Two scenarios are considered. In the first scenario, localized illumination adapted to occupancy and light sensor inputs is considered to provide a default average illuminance value of $W_o = 500$ lx over an occupied zone and $W_u = 300$ lx over an unoccupied zone, with light sensor reference set-points defined accordingly. In the second scenario, we consider personal control wherein the light sensor set-points are modified in order to satisfy user illumination personal control requests.

In the model, when all the luminaires are set to 0.85 an average illumination of 500 lx is achieved. The office has windows on one side of the room for daylight. A clear sky daylight model is considered in the simulations. The light sensors send their measurement every one second to the controller. We model asynchronous behavior of the sensors by adding a random delay with value between 0 and 1 in the initialization time. The proposed controller waits for all the sensor measurements before computing the new dimming level while the stand-alone controller evaluates the dimming level once it receives the associated sensor measurement. The gains of the stand-alone controller are chosen as in [11] as $\alpha_m = 1/G_{m,m}$ and $\beta_m = 1$.

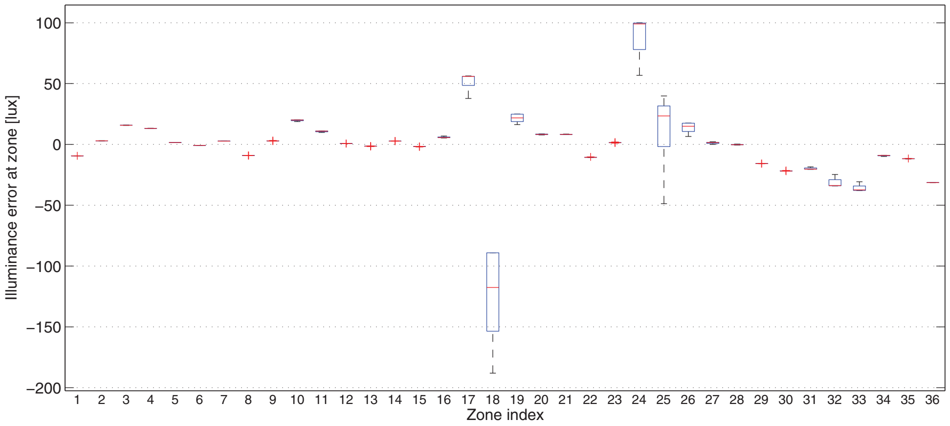

Fig. 12. Illuminance error at each zone with the reference stand-alone controller, minimum approach (1000 simulations). (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

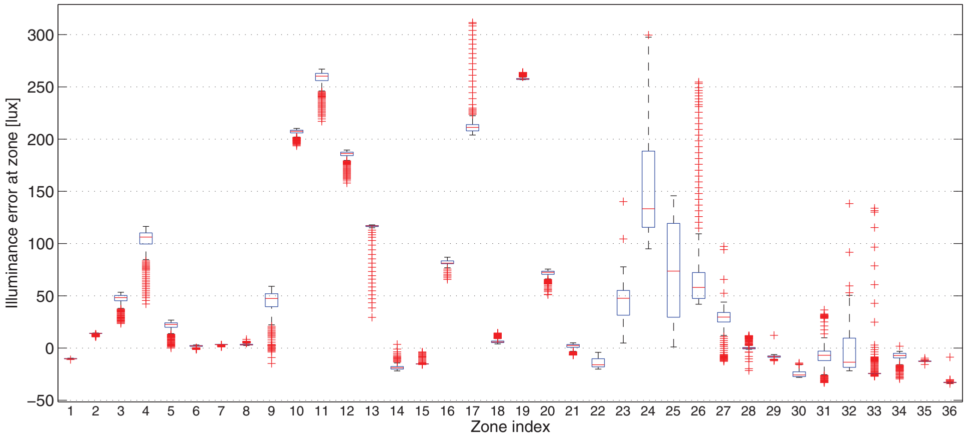

Fig. 13. Illuminance error at each zone with the proposed controller, minimum approach (1000 simulations). (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

4.2. Sensor-driven lighting control

4.2.1. Overshoot/undershoot and settling time

We first show in Fig. 3 the transient period of the two controllers, showing as an example the illuminance value over zone 17, which goes from local unoccupancy to occupancy at $t = 0$. In this simulation there is daylight at 10 am. It is clear that the constrained solution shows no overshoot/undershoot while the stand-alone controller has overshoot of approximately 18% and undershoot of approximately 10%. The overshoot and undershoot are respectively defined as the maximum and minimum values in the transient response compared to the final steady-state value.

Secondly, we consider statistical behavior with a run of 1000 simulations starting from zero state, when all the luminaires are off and considering daylight at 10 am. At $t = 0$, an occupancy step is simulated for each zone (i.e. $r_m = r_{o,m}$, $\forall m$), then the overshoot and the settling time are collected for each zone. The settling time is the time that the illuminance needs to reach and remain inside a 5% threshold of the final steady-state value. In these simulations, we vary the gain α_m of all M stand-alone controllers while the gain β_m is left unchanged at 1. In this way, it is possible to see a trade-off between average overshoot and settling time.

In Fig. 4, we plot the average overshoot at each zone comparing the constrained solution with the reference stand-alone controller for three different values of the gain α_m. The proposed controller does not show any overshoot while in some zones the average overshoot obtained with the stand-alone controller is higher than 20%. Moreover, to be close to the overshoot performance of the constrained solution, the gains α_m of the stand-alone controller have to be reduced (see $\alpha_m = G_{m,m}^{-1}/3$ case). Such modification however results in an increase in settling time, as can be seen in Fig. 5. These values, with sensor sampling period chosen to be 1 second, are still small enough for appropriate lighting control behavior. In Table 1, we then show the percentage of zones that reached the steady-state value in 2 s. It is clear that the proposed constrained solution performs better than the reference controller in dealing with overshoot/undershoot and has a small settling time.

4.2.2. Achieved illuminance and energy savings

In this section we evaluate the performance in terms of achieved illuminance and energy savings.

In Figs. 6 and 7, we show respectively the total under-illumination at the workspace and the energy savings over a day with different daylight conditions when all the zones are occupied. The total under-illumination at the workspace is obtained by considering the under-illumination in each zone and aggregating these values. The energy savings are evaluated by comparing with a system with all luminaires fixed at a dimming level of 0.85. In these plots, different values of parameter λ in the constrained solution are considered. From Fig. 7, we can note that the energy savings from the stand-alone controller and the proposed controller are approximately the same, for all the values of λ considered. On the other hand, from Fig. 6 we can clearly see that the total under-illumination is much less that the proposed controller, in particular by choosing $\lambda = 0.5$ and $\lambda = 1$.

4.3. Sensor-driven personal lighting control

In this section we evaluate the performance of the proposed controller in the personal control scenario. In these simulations, we set $\lambda = 0.5$ since from the previous scenario, this choice provides a good trade-off between under-illumination and energy savings.

Consider the following scenario: at $t = 0$ two neighboring zones get occupied while all the other zones are unoccupied and there is no daylight. In particular consider zone 18 and 25 and suppose that the two occupants require 600 lx and 400 lx respectively. In Fig. 8(a)–(c), we show the steady state value of the average illuminance at zones with the minimum, maximum and average approaches respectively as described in Section 3.1. We can observe that with the reference controller for all the three approaches we have 100 lx or more of under-illumination over zone 18, while with the constrained solution we obtain an illumination value close to the desired 600 lx.

To better understand the performance of the proposed controller, under the same occupancy scenario let us consider also the steady-state values of illuminance over zones (Fig. 9) and at light sensors (Fig. 10) and dimming levels of luminaires (Fig. 11) for the maximum approach of setting set-points. In this simulation we consider daylight at 5 pm. In Fig. 9, we can see that the desired illuminance value over zone 18 can be met with the proposed controller, while the stand-alone controller under-illuminates this zone. From Fig. 10, observe the illuminance values at light sensors 36, 45 and 46, which are triggered due to occupancy in zone 18. We can see that the stand-alone controller fails to meet the reference set-points at these sensors, while they are exactly reached with the proposed controller. This is a result of imposing that the illuminance value be no smaller than the set-point as a constraint as well as a penalty term in the cost function of the constrained optimization problem, which enforces the solution to one where the sensor constraints are tightly met. This results in the neighboring luminaires being at a much higher dimming level in the constrained solution compared to the reference stand-alone controller; in particular from Fig. 11 observe the luminaires 25, 26, 34, 35, 37, 55 and 56. This results in a much higher illumination value over zones 18 and 25, as observed from Fig. 9. A consequence of neighboring luminaires being at a higher dimming level is that neighboring zones (e.g. zones 24 and 26 that are neighbors of zone 25) have over-illumination. This amount of over-illumination is not substantially high and likely within a comfort illuminance range acceptable to users [16,26]. These observations however need to be validated with user field tests in realistic office lighting settings.

We now consider simulations to show statistical validity of our results. Consider again the same occupancy scenario but now suppose that the occupant at the 25th zone can select the desired illuminance level at zone with a value in the range (400, 600) lx. The occupant at zone 18 requires again 600 lx. In Figs. 12 and 13 we show the difference between the achieved illuminance and the desired value at zones for the stand-alone controller and the proposed controller respectively. For both control laws, we run 1000 simulations and show the minimum approach. The box plot shows the median as the red line, the 75th and 25th percentile values as the box boundaries, and points outside 1.5 times the size of the box are displayed individually by red crosses. From Fig. 12, we can observe that for all the illuminance values required at zone 25, the reference controller shows a large under-illumination at zone 18, while with the proposed controller the desired value is met in each simulation. Across simulation instances, note from Fig. 13 that the illuminance values achieved in zones that are neighboring to zone 25 depend on the desired illuminance value over zone 25. This is because of the intrinsic design of the proposed controller wherein neighboring luminaires also would dim to satisfy the reference set-points of light sensors over a zone.

5. Conclusions and discussion

We presented a multi-variable feedback controller to perform personal control with daylight and occupancy adaptation in a lighting system. Methods for specifying the light sensor set-points were considered to account for user illumination personal control requests. The centralized controller was designed by optimizing a weighted sum of squares of the illumination error and square of the power consumption, with illumination constraints at the light sensors and physical constraints on luminaire dimming levels. The performance of the proposed method was evaluated via simulations and compared with a benchmark stand-alone controller in an open plan office lighting model. As compared to the reference controller, the proposed controller was found to have lesser under-illumination while achieving similar energy savings under different daylight conditions in the sensor-driven control scenario. Finally, the proposed method has better performance even in terms of achieving the reference set-points in the sensor-driven personal control scenario.

The scope of this paper was limited design of personal control algorithms and performance evaluation via simulations. A next step would be to study the influence of various control system parameters as well as system performance indicators from a user experience perspective. These topics should be studied in future and validated with user field tests in office lighting settings.

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