

Daylight integrated illumination control of LED systems based on enhanced presence sensing

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ABSTRACT

Light emitting diodes (LEDs) are considered to become the dominant source of illumination in the future, offering long life times, energy efficiency and flexible tunability. The flexibility of adapting LED parameters offers multiple degrees of freedom in designing LED based lighting systems. In this paper, we consider energy-efficient illumination control design of LED based lighting systems in office spaces. Our goal is to determine the optimum dimming levels of the LED sources so as to minimize the power consumption while rendering (i) uniform illumination at a given illumination level in workspace regions that are occupied, and (ii) a minimum illumination level of lower value in unoccupied regions, while taking daylight distribution over the workspace plane into account. In order to determine occupant locations, we present an ultrasound array sensor solution with enhanced presence detection capability. We further propose a method to estimate and disaggregate illumination contributions of daylight and the different LED sources at the workspace plane. The performance of our proposed control solution is evaluated under different occupancy scenarios.

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1. Introduction

Energy efficiency is one of the design drivers of smart lighting systems and more generally of green buildings. In office buildings, lighting alone constitutes about 25–35% of the total energy consumed [9]. Energy consumption of a lighting system may be addressed by incorporating energy-efficient light sources, properly designing lighting controls and controlling lighting systems based on sensing information regarding occupancy and daylight.

Light emitting diodes (LEDs) are an attractive choice as an energy-efficient illumination source that can provide long life times, dynamic lighting effects and greater design flexibility. The flexibility in controlling individual LEDs can be used to render dynamic lighting in LED based systems while realizing savings in energy.

In this paper, we consider illumination rendering from an LED based lighting system in an office setting. The lighting system under consideration comprises of multiple LED based light sources, photosensors and a presence sensor. We are interested in the multiple facets that contribute to energy-efficient system design: enhanced presence sensing, and illumination control optimization that takes into account presence information and daylight contributions. Illumination control relates to the determination of LED dimming

levels according to some design criteria. In this paper, our design goal is to minimize the power consumption by determining the optimum dimming levels of LEDs so as to render an illumination level of L_o in occupied regions and a minimum illumination level of L_u elsewhere, while taking into account daylight illumination over the workspace plane. The illumination levels L_o and L_u are chosen according to office workspace lighting recommendations [8].

Occupied regions are determined using a presence sensor. In particular, we propose an ultrasound based array sensor to determine presence and location of occupants. Ultrasound sensors provide an active way to monitor presence in large volumetric spaces and are potentially more sensitive than passive infrared sensors. Ultrasound sensors have been used for occupant detection in the past [7,13,18,23]. Past solutions were single element sensors based on either time-of-flight or Doppler measurements, and only provided binary room-level occupancy information.

Our array sensor solution comprises of a transmitter that sends out periodic bursts of sinusoids. The receiver comprises of a linear array of sensors that processes received echoes corresponding to every two consecutive transmit pulses to derive locations of occupants. The various signal processing steps involved in obtaining location of multiple occupants are described in Section 2.

Several studies [2,10,21] (and references within), [25] have shown that considerable energy savings can be realized by designing lighting systems that are adapted to the presence of occupants. In its simplest form, occupancy information is used to control an entire lighting system in a room to provide illumination only when

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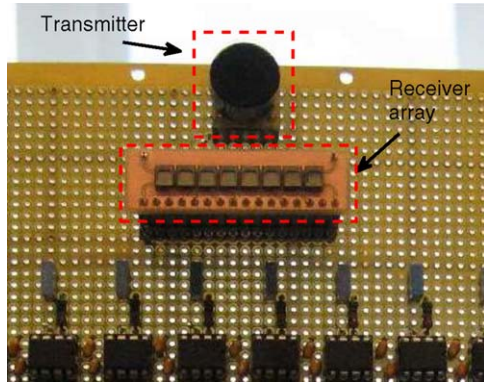


Fig. 1. Ultrasound array sensor solution.

the room is determined to be occupied. The presence of occupants is determined by simple motion detectors, e.g., passive infrared sensor, ultrasound sensor or a combination thereof. The information that is output from these sensors is a binary value indicative of whether the monitored space is occupied or not. Such information can only be used to realize energy gains when the monitored space is empty in its entirety, and thus has limited energy saving potential. For instance, in a multi-occupant office, if there is only a single person present, the entire lighting system would be on. Further, it is not possible to exploit the degrees of design freedom that an LED system has to offer.

The problem of illumination rendering in LED based systems has been considered in [19,26]. The goal in [19] was to determine the dimming levels required to create specific illumination patterns using a mean-squared error approach. In [26], the design of the LED radiation pattern was studied with the goal of uniform illumination rendering. Such illumination control approaches require that individual LEDs be controllable. Methods for doing so using code division multiplexing and frequency division multiplexing have been proposed in [16] and [27,28] respectively. Strategies for integrated daylight–artificial light control based on computational models were presented in [12]. Field tests showing the savings obtained by daylighting offices have been reported in [15]. Lighting control design that accounts for occupant preferences and building operator utility was considered in [22].

The paper is organized as follows. In Section 2, we present the design details of the ultrasound array sensor and present results of localization experiments conducted in an office test room. The illumination control problem is formulated in Section 3, and takes location of occupants into account. We describe methods to disaggregate illumination contributions of daylight and the LED based light sources at the workspace plane. Numerical results showing the performance of the proposed illumination control solution are presented in Section 4. Conclusions are drawn in Section 5.

2. Enhanced presence sensing solution

In this section, we describe our array sensor solution for enhanced presence detection. The array sensor comprises of an ultrasound based transmitter and a co-located linear array of M receivers as depicted in Fig. 1. The transmitter and receiver are assumed to be omni-directional. The transmitter sends out a periodic pulse train, comprising of sinusoids of duration T at frequency f_c ($=40$ kHz), with a pulse repetition interval PRI , as shown in Fig. 2. The transmitted waveform in the interval $0 \leq t \leq T$ can be written as

$$s(t) = \Pi\left(\frac{t}{T}\right) \cos(2\pi f_c t)$$

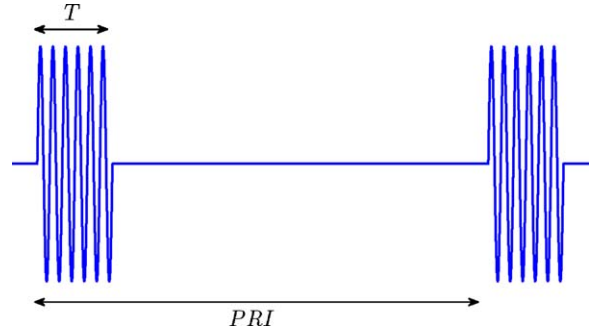


Fig. 2. Short duration pulse in transmitted waveform.

with

$$\Pi(t) = \begin{cases} 1 & \text{if } 0 \leq t \leq T \\ 0 & \text{otherwise.} \end{cases}$$

The parameters T and PRI are determined by the range resolution, ΔD , and the maximum unambiguous range, D . The range resolution is the minimum separation in distance between two moving sources that the sensor can resolve. The maximum unambiguous range is the distance beyond which objects are seen at a distance modulo D . Choosing $\Delta D = 0.344$ m (corresponding roughly to the linear distance a human object would occupy) and with the speed of sound as $v_s = 344$ m/s, we have $T = 2\Delta D/v_s = 2$ ms. We chose $D = 5$ m, which is a reasonable coverage range for typical office scenarios. The round-trip time from the sensor to an object at distance D is then $2D/v_s \approx 30$ ms. The parameter PRI is hence chosen to be 2 ms + 30 ms = 32 ms.

The receiver array has sensor elements that are separated by a distance that is no more than half the wavelength. This ensures that no grating lobes are observed within the scanning range. At the receiver array, the following processing steps are employed:

- i. Range processing: The first step is to determine the range of moving sources from the sensor. Towards this end, we consider the difference of received signals from two consecutive transmit pulses. Echoes from static objects result in the same contribution in received signals from consecutive transmit pulses, and hence the difference would be zero. Echoes from moving sources on the other hand result in a non-zero difference signal. Signal power is computed per range bin based on the difference signal. A moving source is determined to be present at a certain range bin if the computed signal power exceeds a detection threshold. The detection threshold is set by computing the noise power using measurements in quiet periods.
- ii. Direction-of-arrival (DoA) processing: We then compute the DoA of the moving sources. Here we employ an iterative DoA algorithm to deal with the fact that the number of sources is not known a priori. At each iteration step, we compute a list of DoAs obtained using a diagonal loading method [5].
- iii. Source tracking: We use a movement model for tracking occupants inside the office. This model is based on estimating the current location of an occupant by using an extrapolation filter over the previous locations. A higher score is associated with a location estimate obtained from a current measurement if it is close to the estimated location from extrapolation. Scores are accumulated over time and if the accumulated score exceeds a threshold, an occupant is declared to be present. This also helps in mitigating multipath to an extent since low scores tend to get associated with location estimates due to multipath reflections.
- iv. Multipath mitigation: The key observation we use is that in a number of instances, multipath results in estimated locations

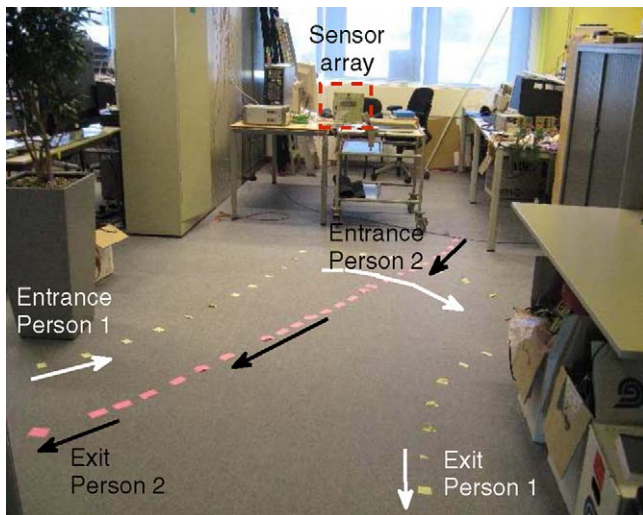


Fig. 3. Test room and trajectory of the occupants.

that are infeasible. For example, multipath may result in estimated locations that fall outside the dimensions of the room and can be discarded.

The signal processing techniques involved in the steps above have been described in detail in [3]. Steps (i)–(ii) together result in the location of occupants in a room, while steps (iii) and (iv) are used to improve the location estimates and determine movement trajectories of occupants. These steps lead to a reliable presence sensing and localization solution. Detection errors may still occur in exceptional cases when an occupant is blocked from the view of the array sensor, or manages to be still for a prolonged duration of time. Such situations may however be suitably handled in the lighting controller, e.g., by using a timer, to deal with a few missed detections.

2.1. Experimental results

We evaluate the performance of the array sensor solution in a test office room shown in Fig. 3. The room is 4.5 m in length and 3 m in width. The array sensor, with $M=8$ receive elements, is located at a height of 1.2 m above the ground.

We consider the following scenario with two occupants. The trajectories of the two occupants are depicted on the floor by a number of marked points in Figs. 3 and 4. At the beginning of the experiment, the room is empty. Then, the first occupant enters through one side of the room and walks closely along the trajectory depicted in Fig. 4 marked by stars. When the first occupant reaches the location “A”, the second occupant enters the room and walks closely along the trajectory marked by squares as shown in Fig. 4. Finally, both occupants leave the room.

The results of our experiment are shown in Fig. 5. Points along the trajectories of the first and second occupants in Figs. 4 and 5 are shown by stars and squares respectively. The estimated trajectories of the two occupants are shown by (red) asterisks and (green) crosses. As can be seen, the estimated locations closely match the real locations. The (blue) crosses represent locations which have been discarded as multipath.

The maximum number of occupants that can be localized, in theory, is limited by the number of elements of the linear array. Furthermore, occupants that are too close to each other may be seen as one object. These situations are not limiting from the viewpoint of lighting control in offices. The functionality to localize a few (3–4) occupants suffices; for larger number of occupants dis-

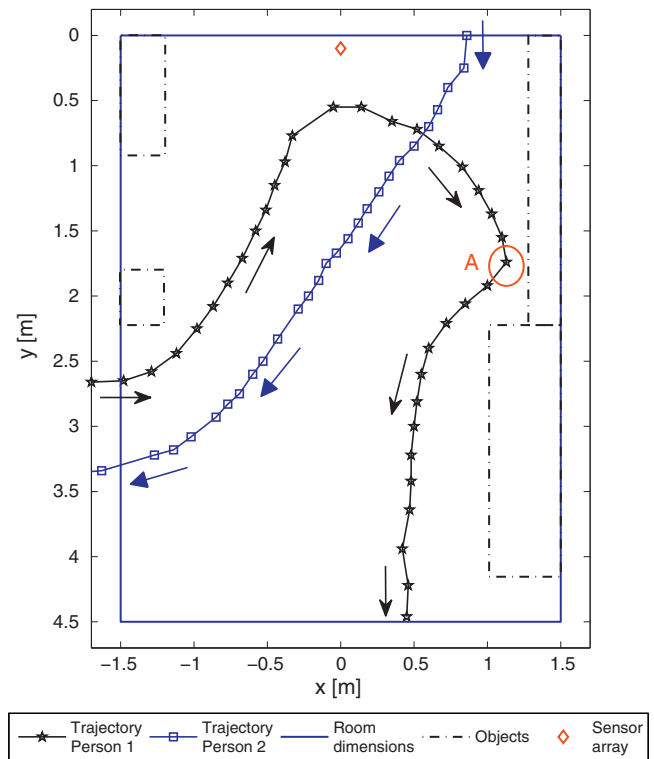


Fig. 4. Plot of the room and trajectory of the occupants.

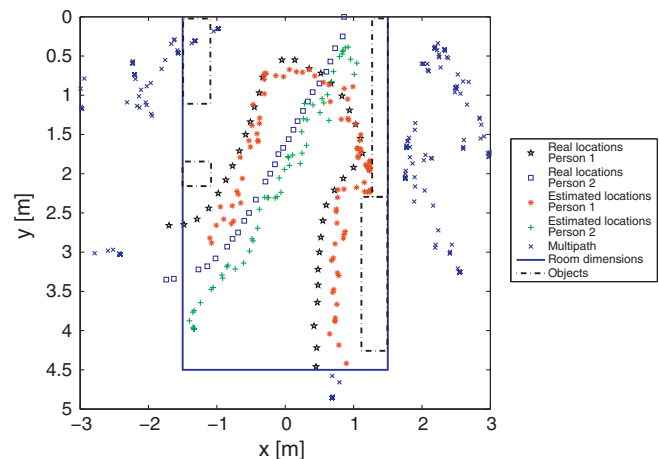


Fig. 5. Experimental results.

tributed across the room, it would in any case be desirable to illuminate the entire room. Further, if two occupants are determined as a single object due to their spatial proximity, this is not a problem since the region in the vicinity would be illuminated under the lighting control solution discussed in the next section.

3. Lighting control solution

We consider an LED based lighting system with a total number of N LED based light sources and K photosensors arranged on the ceiling. An example configuration is shown in Fig. 6, where a number of LEDs together comprise an LED based light source.¹ In certain con-

¹ We shall use the terms “LED based light source” and “LED source” interchangeably to refer to a source that is based on a collection of embedded LEDs.

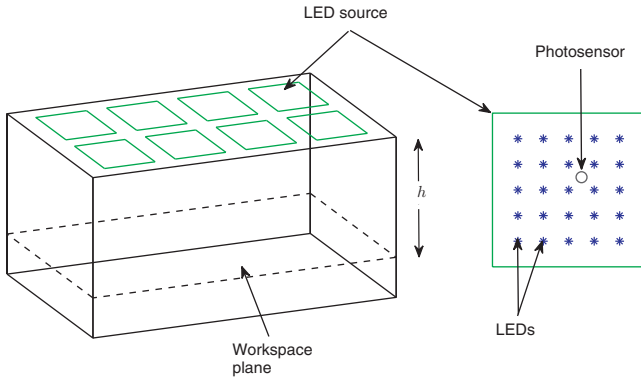


Fig. 6. LED based lighting system.

figurations, the photosensor could be coupled to the light source, in which case $K=N$. The location of the i th LED source is given by coordinates (x_i, y_i) and is assumed to be known from the commissioning plan. We consider a simple illumination model for the LED source. The total illuminance achieved from an LED source is the aggregated superposition of the illuminance from individual LEDs in that source. For the i th LED source, let (x_{iv}, y_{iv}) be the coordinates of the v th LED, $v = 1, \dots, V$. Employing the widely used generalized Lambertian function [17,20,24] to model the far-field illumination pattern of an LED, the illuminance achieved at a location (x, y) in the workspace plane (at a distance h from the ceiling) from an LED source located at (x_i, y_i) is thus given by

$$E_i(x, y; h) = A \sum_{v=1}^V \left[1 + \frac{\|(x, y) - (x_{iv}, y_{iv})\|_2^2}{h^2} \right]^{-(m+3)/2} \quad (1)$$

with

$$A = \frac{(m+1)A_0}{2\pi h^2},$$

where A_0 is the luminous flux of the light and $m > 0$ is the Lambertian mode. This mode is related to the semi-angle of the light beam at half power, $\Phi_{1/2}$, by

$$m = -\frac{\ln(2)}{\ln(\cos(\Phi_{1/2}))}.$$

We assume a frequency division multiplexing based system [28] wherein each LED source is assigned a distinct frequency. The illumination intensity of the LED source is controlled using pulse width modulation (PWM) [11]. The duty cycle of the PWM waveform is the dimming level of the LED source. Hence, the average power consumed by the i th LED source at dimming level d_i over one waveform cycle is

$$P_i(d_i) \approx d_i P_{\text{on}}, \quad (2)$$

where P_{on} is the power consumption while the source is on (the approximation in (2) is under the assumption that the power consumption in the off state is negligibly small). Denote by \mathbf{d} , the $N \times 1$ dimming vector, given by

$$\mathbf{d} = [d_1, d_2, \dots, d_N],$$

where $0 \leq d_i \leq 1$ is the dimming level of the i th LED source. The value $d_i = 0$ means that the LED is dimmed off while $d_i = 1$ represents that the LED is at its maximum illumination. In practice, d_i takes values from a finite discrete set of values $\{l_1, l_2, \dots, l_Q\}$, where the l_q 's represent dimming levels and $l_1 = 0, l_Q = 1$.

The workspace plane is parallel to the ceiling at a distance h from it, and is the plane over which a particular illumination rendering is desired. For clarity of exposition, we will not introduce a

z -coordinate to distinguish the two planes since the difference will be clear from the context.

The office is additionally equipped with a presence detection sensor as the one described in Section 2. Assume there are J occupants in the office. The locations (x_j, y_j) , $j = 1, \dots, J$ of occupants in the office are determined by the presence detection sensor. Define the occupied region R_o as the collection of all points that are within a distance r_0 from an occupied location,

$$R_o = \{(x, y) : \|(x, y) - (x_j, y_j)\|_2 \leq r_0, \quad j = 1, \dots, J\}, \quad (3)$$

and its area by Ω . The constant r_0 may be chosen as per workspace norms and occupant visual comfort.

We desire uniform illumination at level L_o in the occupied region R_o . In the unoccupied area, it is desired to have a minimal illumination level of L_u . Levels L_o and L_u are chosen as per office illumination norms. In practice, uniform illumination is in the sense that variations in the illumination level about the value L_o must be below a certain threshold, C_o . This notion is analytically captured by illumination contrast. Denote the total illuminance at a point (x, y) in the workspace plane (at distance h from the ceiling) by $E_T(x, y; h; \mathbf{d})$, when the dimming levels of the LED sources are given by dimming vector \mathbf{d} . The illuminance contrast between $E_T(x, y; h; \mathbf{d})$ and L_o is defined as [1],

$$C(E_T(x, y; h; \mathbf{d}), L_o) = \frac{E_T(x, y; h; \mathbf{d}) - L_o}{L_o}. \quad (4)$$

The total illuminance is the combined illumination contribution of daylight and the LED sources. Denoting by $D(x, y; h)$ and $E_i(x, y; h)$ the illuminance in the workspace plane at location (x, y) and a distance h due to daylight and the i th LED source respectively, we have

$$E_T(x, y; h; \mathbf{d}) = D(x, y; h) + \sum_{i=1}^N d_i E_i(x, y; h). \quad (5)$$

Given that the illumination levels vary about L_o , we furthermore require that the mean illumination level over R_o be L_o .

The goal is to determine the dimming levels of the LED sources so as to achieve the desired illumination rendering with minimum power consumption. This illumination control problem can be mathematically formalized as follows. We want to determine the optimum dimming vector \mathbf{d}^* that solves

$$\mathbf{d}^* = \arg \min_{\mathbf{d}} \sum_{i=1}^N P_i(d_i) \quad \text{s.t.} \quad \begin{cases} |C(E_T(x, y; h; \mathbf{d}), L_o)| \leq C_o, & \forall (x, y) \in R_o \\ \frac{1}{\Omega} \int_{(x, y) \in R_o} E_T(x, y; h; \mathbf{d}) dx dy = L_o \\ E_T(x, y; h; \mathbf{d}) \geq L_u, & \forall (x, y) \notin R_o \\ d_i \in \{l_1, l_2, \dots, l_Q\}, & i = 1, \dots, N. \end{cases} \quad (6)$$

Some comments are due regarding feasibility of (6). If the contribution of the daylight illumination level is higher than $L_o(1 + C_o)$ at certain points in the workspace plane, then the first constraint cannot be met if these points lie in R_o . This is so because, even with all the LED sources in off state, the total illumination level (which is the contribution of the daylight level) would be higher than $L_o(1 + C_o)$ at certain points, and thus the contrast would be greater than C_o . To deal with this, we discard all points that have a daylight illumination level higher than L_o from our optimization problem. In certain cases, high daylight leads to an undesirable glare which affects visual comfort levels of occupants. This may be accounted

by taking glare control, which can be achieved for instance through electronic blinds, into our problem formulation.

Before solving (6), the following aspects need to be addressed: Given that illumination measurements are made using photosensors in the ceiling, how do we determine illumination values at various points in the workspace plane? How do we determine how much illumination comes from daylight and individual LED sources, given illumination values at locations in the workspace plane?

Our solution involves a configuration step and signal processing techniques. During configuration, light intensity measurements are taken at a number of points in the workspace plane as well as at the photosensors on the ceiling. These measurements may be taken by having the light sources turned on at dimming levels specified by vector \mathbf{d}_s . Correspondingly, let the measurements of the photosensor at location (x, y) in the workspace plane and the k th photosensor in the ceiling be $E_T(x, y; h; \mathbf{d}_s)$ and $E_T(\tilde{x}_k, \tilde{y}_k; 0; \mathbf{d}_s)$ respectively. Now based on these signal measurements, we obtain estimates of $\{E_i(x, y; h)\}$ and $\{E_i(\tilde{x}_k, \tilde{y}_k; 0)\}$. This is done by estimating the frequencies of the sources using, for instance, the techniques described in [27] or [28]. Since the duty cycles are known a priori, the summed signal contribution of the LED sources is subsequently determined. Estimates of $D(x, y; h)$ and $D(\tilde{x}_k, \tilde{y}_k; 0)$ can then be obtained after subtracting the total signal contribution of the LED sources from the received signals. Based on sufficient number of illumination measurements in the workspace plane and the ceiling, an illumination mapping is created by which it is possible to determine illumination values at different points in the workspace plane based on measured values at the photosensors in the ceiling.

During normal operation, we have the measurements $E_T(\tilde{x}_k, \tilde{y}_k; 0; \mathbf{d})$, $k=1, \dots, K$, at the K photosensors. Using the procedure explained earlier, we first determine estimates of $D(\tilde{x}_k, \tilde{y}_k; 0)$ and $E_i(\tilde{x}_k, \tilde{y}_k; 0)$, $i=1, \dots, N$. Then using the illumination mapping table created in the configuration step, the set of estimated illumination values at the ceiling are mapped to obtain estimates of $D(x, y; h)$ and $E_i(x, y; h)$ for all points (x, y) of interest in the workspace plane.

We now turn our attention to solving (6). Observe that the objective function as well as the constraints is linear in the optimization variables $\{d_i\}$. The optimization problem is thus a linear programming problem [14] and can be solved using a Simplex algorithm [6]. The computational complexity of the Simplex algorithm is $3(N+W)$ [14], where W is the number of constraints in the optimization problem resulting when (6) is discretized and slack variables are incorporated [4]. On the other hand, a full-search has exponential complexity of N^Q , where Q is the number of dimming levels.

4. Experimental results and simulations

We now present simulation results showing the performance of the proposed control algorithm, labeled ODA. The baseline control algorithm for comparison is one that optimizes the LED system so as to provide uniform illumination across the entire room taking room-level occupancy into account. The underlying optimization problem is one where R_0 in (6) covers the entire workspace plane of the office room. A simplex algorithm is used to obtain the dimming levels and is labeled UIA. We shall assume parameter values of $L_0 = 600$ lx, $L_u = 300$ lx and $C_0 = 0.3$, consistent with workspace office lighting norms [8]. The parameter $r_0 = 1$ m, and an 8-bit uniform dimming corresponding to $Q=256$ is assumed. We consider two occupancy scenarios, with the location of users being determined by the presence detection sensor described in Section 2.

We consider an office test room of length 4.5 m and width 3 m, with the workspace plane located about 2 m from the ceiling. There are $N=8$ LED sources on the ceiling in the configuration shown in Fig. 6, comprising of 25 LEDs arranged in a 5×5 uniform square

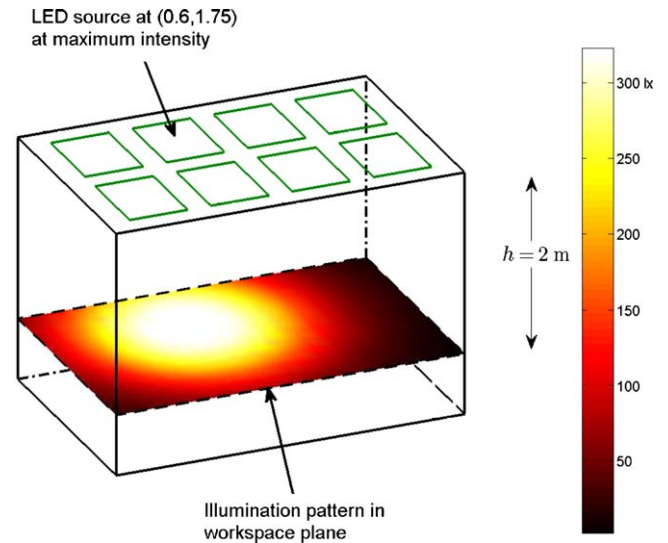


Fig. 7. Illumination pattern of an LED source.

grid with 0.1 m of separation between LEDs. The spacing of the LED sources is 0.9 m along the length and 1.2 m along the width, as measured between the center of the grid. The individual LED is of type LUXEON model [17] that has a Lambertian radiation pattern with a half-power beam angle of 60 degrees and a maximum intensity of 14.3 lx. As an example illustration, the illumination pattern in the workspace plane when the LED source located at (0.6, 1.75) is at full dimming level is shown in Fig. 7. We assume that the dimming level of the source is tunable at a group level, i.e. LEDs within a source are at the same dimming level. Extension to the case where all individual LEDs are tunable is straightforward. In Fig. 8, we show the spatial distribution of daylight across the workspace plane. A window was located at one end of the room, which is reflected in the high illumination values seen in the top part of Fig. 8.

In the first occupancy scenario, we consider a single user. The user is located at the coordinate (0, 2.25). For this setting, we show the resulting illumination pattern under ODA in Fig. 9 and the corresponding dimming levels of the LED sources in Fig. 10. Note from Fig. 9 that points close to the window have illumination levels greater than 600 lx and comprise the region that is unfeasible. Correspondingly, LED sources close to the window are thus dimmed off as seen in Fig. 10. In Fig. 11, we show the power savings for different

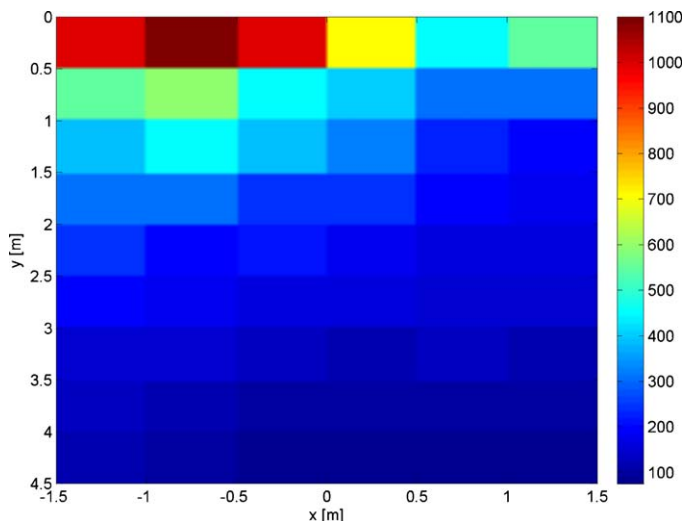


Fig. 8. Daylight distribution (in lx).

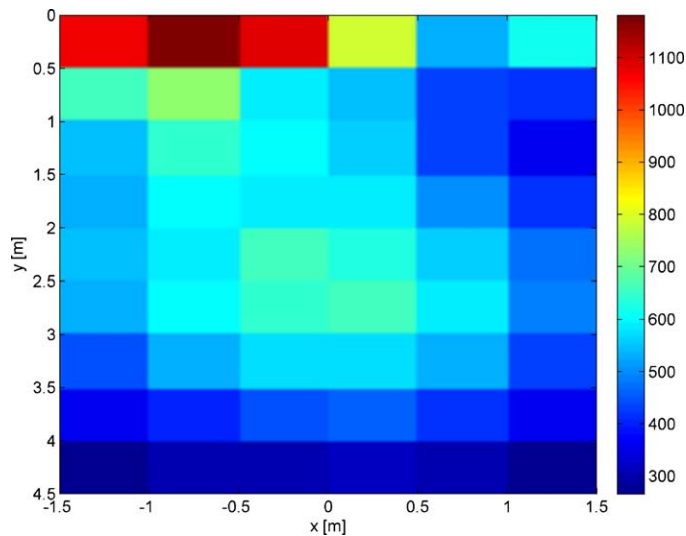


Fig. 9. Illumination pattern obtained using ODA for an occupant located at the center of the room.

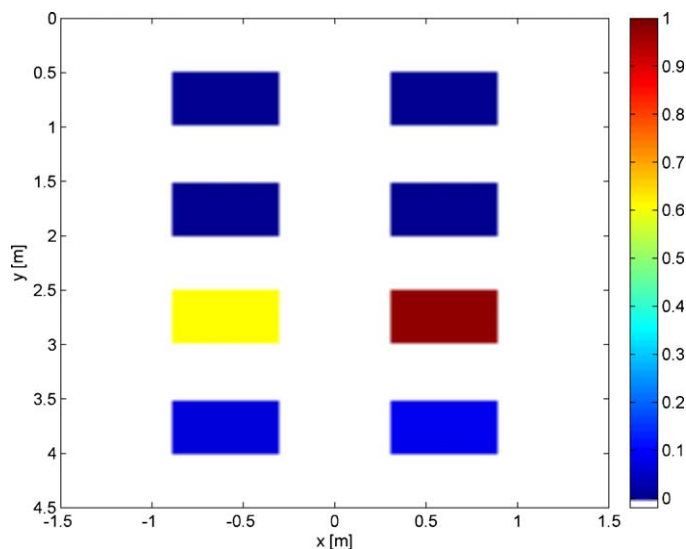


Fig. 10. Optimized dimming levels under ODA of LED sources for an occupant located at the center of the room.

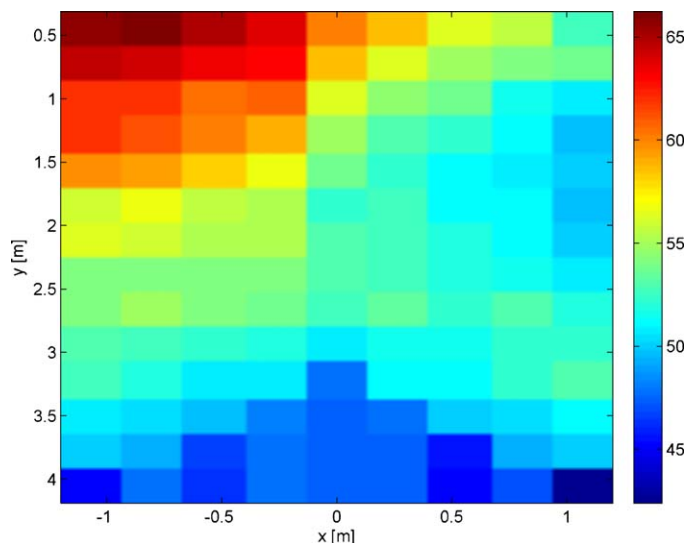


Fig. 11. Power savings for different locations of the occupant in the room.

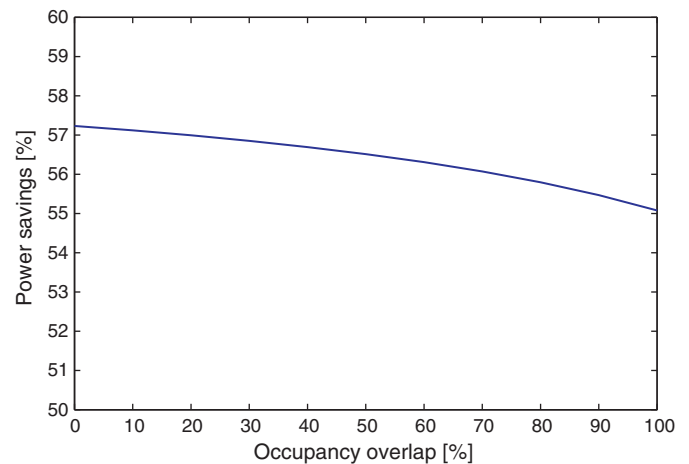


Fig. 12. Power savings for different levels of occupancy overlap for two occupants.

occupancy locations of the user in the room. Note that the savings are greater at occupant locations close to the window, more specifically, at locations where the daylight levels are higher. This means that the contribution required from the LED sources to meet the illumination requirements at such points is minimal, translating to power savings.

In the second occupancy scenario, we consider two occupants located at (0, 1.5) and (0, 3). Here we analyze the power savings for different amounts of occupancy overlap, i.e. the fraction of time that both occupants are at their workspace. These results are depicted in Fig. 12. The largest gain in power savings is when only a single occupant is present at any given time, with the savings decreasing as the overlap increases. However, note that the power saving does not change substantially with occupancy overlap. This is since a large portion of the region around the occupant located at (0, 1.5) is already adequately illuminated by daylight and the contribution required from the LED sources is minimal. In general, for lower daylight levels and larger room sizes, we would expect greater power savings at low levels of occupancy overlap.

5. Conclusions

We developed a framework for energy-efficient illumination control of LED systems that takes into account location of occupants and daylight distribution. We showed that our designed ultrasound array sensor provides accurate localization information. This information is input to the illumination control algorithm to optimize dimming levels of the multiple LED sources in order to achieve the desired illumination rendering. We then considered different occupancy scenarios and showed that substantial energy savings can be obtained using our proposed strategy. Further work will involve extensive field tests to understand the impact of specific occupancy patterns on the energy savings that may be realized.

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