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Sensor-driven, human-in-the-loop lighting control

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Smart indoor lighting systems use occupancy and light sensor data to adapt artificial lighting in accordance with changing occupancy and daylight conditions. Such systems can be designed to reduce lighting energy consumption significantly. However, these systems cannot account for individual user preferences at the workplace in real time. We propose a sensor-driven, human-in-the-loop lighting system that incorporates user feedback in addition to occupancy and light sensor inputs. In this system, luminaires transmit unique visible light communication identifier signals. By processing the image captured by a smartphone camera, a user obtains two pieces of information: visible light communication identifiers of luminaires in the vicinity and average image pixel value. A control algorithm is designed that incorporates these user inputs along with occupancy and light sensor inputs to determine the dimming levels of the luminaires to achieve illumination levels acceptable to users. We compare the performance of the proposed lighting control system with a sensor-driven lighting control system in an office test bed.

1. Introduction

Lighting meets the basic illumination needs of users in an indoor space. Lighting constitutes a major portion of the electrical energy consumption in commercial buildings. The design of lighting systems has thus been done with the objectives of meeting illumination requirements of users and reducing energy consumption. One aspect of lighting design is lamp technology and optics. The other aspect is controls, which is the broad scope of this work.

Considerable attention in lighting controls has been paid to realizing energy savings. Advanced lighting control systems use occupancy and light sensors to adapt the amount of artificial lighting to occupancy and daylight conditions to save energy. For instance, lighting systems with granular control in open offices offer a higher illumination level in occupied zones and a lower illumination value in unoccupied zones. The illumination contribution from artificial lighting is adapted so that the total illuminance is above a required illumination value. For instance, the European norm for office lighting BS EN 12464-1 specifies an average illumination of 500 lx in occupied workplaces and an average illumination of 300 lx in unoccupied workplaces. To provide feedback on occupancy status and illumination value to the lighting controller, occupancy and light sensors are used. Using occupancy and light sensor data,
the light output of luminaires in the lighting system is adapted to meet the required illumination values with low energy consumption.\textsuperscript{7–9}

In lighting control systems, light sensors are typically located at the ceiling to measure the illumination at the workplace.\textsuperscript{5} This configuration benefits from simplified placement, installation and wiring of sensors to the luminaire’s power connection. On the other hand, since the sensors are located at the ceiling, sensor measurements do not correspond to the illumination at the workplace. In order to map the illumination measured at the workplace to the ceiling light sensor measurement, a calibration phase is used. However, this calibration phase has limitations. A simple calibration approach\textsuperscript{5} determines the mapping between the illumination value at the workplace and at the ceiling light sensors using only the electric light. In such a system, changes in daylight and/or reflectance changes at the workplace can adversely impact the performance of the system leading, for instance, to under-illumination over workplaces.\textsuperscript{10,11}

To address the problem of under-illumination, different approaches have been proposed. In one approach, light sensors were placed at the workplace. While such a sensor system configuration is effective in meeting workplace target illumination, it is limited in situations where the wireless link between the sensors and controller degrades and/or the sensor field of view is obstructed. To address this, a sensor system with both ceiling and workplace sensors has been proposed.\textsuperscript{14} Approaches using visible light communication (VLC) have been proposed\textsuperscript{15,16} using ceiling sensors to disaggregate the daylight and artificial light components in order to improve illumination. Such systems still do not take into account individual user illumination preferences in real time. While there have been pilot studies that have shown the benefits of incorporating user preferences in lighting,\textsuperscript{17,18} there is limited work on incorporating user preferences in lighting control system design.

Thus, past work has either considered sensor-driven lighting controls or has considered lighting systems that address the relation between illumination and user satisfaction. The former work has the limitation that the lighting system lacks awareness of user preferences and satisfaction with achieved workplace illumination. There is limited work on lighting control system design where both sensor feedback and user feedback on satisfaction with achieved workplace illumination are accounted for.

We introduce a human-in-the-loop component in a sensor-driven lighting control system. This human-in-the-loop component consists of a user with a smartphone who can provide feedback on his/her illumination requirements with respect to the achieved illumination. In order to enable this, we consider luminaires that transmit VLC identifiers. The user captures images around the workplace and derives two pieces of information. One, the VLC identifiers of luminaires in the vicinity are obtained. This information indicates to the lighting controller which luminaires to control to meet illumination requirements of a particular user. Second, the average image pixel value is fed back to the controller. This is used to adapt the ceiling sensor set points. Together with occupancy and light sensor data, this information is used by the controller to dim luminaires in order to meet illumination preferences of the user that are perceived to be satisfactory.

In Section 2, we describe the lighting system under consideration. The camera-based VLC is described in Section 3. In Section 4, the lighting controller is presented showing the human-in-the-loop enhancement. The proposed lighting control system is evaluated in Section 5 in an office space. Conclusions are drawn in Section 6.
2. System description

We begin by presenting the basic elements of a sensor-driven lighting control system in Section 2.1 and then describe the human-in-the-loop sensor-driven lighting control system in Section 2.2.

2.1. State-of-the-art lighting control system

A sensor-driven office lighting system with sensors co-located at each luminaire is depicted in Figure 1. Each luminaire at the ceiling has an occupancy sensor and a light sensor and is connected to a central controller. For each control cycle, occupancy status and illumination values are used by the central controller to adapt the dimming levels of the luminaires to occupancy and daylight changes. An example lighting control algorithm that will be used for performance comparison is described later in Section 4.2.

In office applications, the horizontal illumination at the workplace is of interest and is generally measured at desk height. We assume that the office space is divided into physical zones, with a workplace being part of a physical zone.

The illumination value sensed by the light sensor is the total contribution from all light sources (artificial light, daylight, etc.) reflected back from the workplace. However, the measured value at the ceiling is not the illumination value at the workplace. A calibration phase is required to map the illumination value at the workplace to the value at the ceiling light sensor.

Consider a lighting control system with \( M \) luminaires in the office room. During calibration, assuming no illumination contribution from daylight or external light sources, the illumination contribution matrix \( A \) is determined

\[
A = \begin{bmatrix}
A_{1,1} & \cdots & A_{1,M} \\
\vdots & \ddots & \vdots \\
A_{M,1} & \cdots & A_{M,M}
\end{bmatrix}
\]

where \( A_{m,n} \) is the illumination contribution sensed by ceiling light sensor \( m \) when
luminaire \( n \) is at maximum light output while other luminaires are completely off.

A linear mapping of the illumination value at the workplace and the illuminance value at a ceiling light sensor is obtained using the illumination contribution matrix \( A \) and is used to determine the reference set point at ceiling light sensor \( m \), given by

\[
c^*_m = \sum_{n=1}^{M} A_{m,n}, \quad \forall m
\]

The target reference set point \( l^*_m \) for each ceiling light sensor \( m \) is then specified as

\[
l^*_m = \begin{cases} 
500 \frac{c^*_m}{W_{\text{ave}}} & \text{if zone under luminaire } m \text{ is occupied} \\
300 \frac{c^*_m}{W_{\text{ave}}} & \text{otherwise}
\end{cases}
\]

where \( W_{\text{ave}} \) is the average illumination value measured over the entire area when all luminaires are set to their corresponding maximum light output. In equation (2), the set points were computed to correspond to target workplace illumination levels conforming to European norms for office lighting that suggest occupied zones have 500 lx on average, while unoccupied zones have 300 lx on average. If the entire office space is unoccupied, the luminaires are turned off.

### 2.2. Proposed lighting control system

The proposed lighting control system with the human-in-the-loop component is shown in Figure 2. The user (i.e. human in the loop) uses a smartphone to provide information to the lighting control system by capturing images during two phases: (1) multiple images at the same position but different orientations are captured using a short exposure time for luminaire detection and (2) multiple images at the same position and orientation are captured using a long exposure time for controlling the illumination at the workspace plane.

When a user is at his/her workplace and desires a change in illumination, he/she captures images using a smartphone camera. Two types of information are derived from processing the camera images. One is the VLC identifiers of luminaires in the neighbourhood.
of his/her workplace. The other is the average image pixel value, which is used to control the illumination at the workplace. Based on the user’s satisfaction with the current illumination value at the workplace, the user can either choose to send an increase or decrease command indicating to the controller that the illumination at the workplace is to be adapted accordingly. The average image pixel value is used by the controller to adapt the light sensor set points in accordance with the increase/decrease control command. The central controller has a predetermined increment/decrement step for each control cycle to ensure smooth dimming level changes within a certain range. If the user is satisfied with the current illumination, he will send a stop command to the central controller to terminate the control process, otherwise, the lighting control process will continue. When the system reaches its maximum dimming level output, a message will be sent to the user to inform him/her that illumination from the lighting system cannot be increased further.

A user with a smartphone thus provides feedback related to the satisfaction with the current illumination value at his/her workplace and provides inputs additional to the occupancy and light sensors to the central controller. If no users provide such feedback, the system is driven solely by sensor inputs. The smartphone thus serves as an additional feedback source and incorporates the human-in-the-loop component so that the lighting controller adapts the light output of the luminaires to occupancy, daylight and user satisfaction with the achieved workplace illumination.

3. Camera-based VLC

This section describes the implementation of a camera-based VLC system where (1) the light output of each LED luminaire in the lighting system is modulated to transmit a unique identifier and (2) smartphone cameras are used to receive and decode the identifier. At the end of the section, an evaluation of this detection process is presented.

3.1. Luminaire modulation

The main functionality of the lighting system is to provide the desired illumination set by the system or the user. Therefore, the modulation scheme has to be chosen such that the average light output of the luminaire remains constant. Amplitude modulation is considered to modulate the light output of each LED luminaire.

The light output of a LED luminaire is controlled by setting its dimming level $0 \leq d(t) \leq 1$, where $d(t) = 0$ and $d(t) = 1$ indicate, respectively, that the luminaire is off and at maximum light output. We propose to modulate the dimming level of a LED luminaire as

$$d(t) = \bar{d} + \Delta d p(t)$$

where $\bar{d}$ is the desired average dimming level, $p(t)$ is a square wave with frequency $f_{Tx}$ and $\Delta d$ is the modulation depth. Note that each LED luminaire in the lighting system has a unique transmitting frequency $f_{Tx}$ that allows for individual identification. To avoid flicker, the transmitting frequency $f_{Tx}$ is above 1 kHz.

An example of the modulation of the dimming level of a LED luminaire is given in Figure 3. The dimming level is modulated with a 1500 Hz transmitting frequency and modulation depth $\Delta d = 0.05$. Here, the desired average dimming level is $\bar{d} = 0.1$.

3.2. Rolling shutter mechanism

In the field of VLC, previous work has shown that a communication link between a LED luminaire and a smartphone, namely camera-based VLC, can be achieved. Danakis et al.22 exploited the rolling shutter mechanism of a CMOS camera to realize a camera-based VLC system. Rolling shutter is
widely used on CMOS cameras in smartphones and works by acquiring the rows or columns of an image sensor array in a sequential way. Without loss of generality, we assume that the rolling shutter mechanism scans the image sensor array across columns. The readout of each column is operated after the readout of the previous column as shown in Figure 4. From Figure 4, it is clear that for a single image frame captured by a CMOS camera sensor, the beginning time of exposure for each column is different (delayed by a multiple of the readout time). The delay of the starting point of exposure between columns can result in image distortion when capturing a fast moving object, but it can be used in VLC to receive modulated signals.

In the absence of daylight, we have the following proportionality holding for the intensity of a given pixel in the nth row of the CMOS camera, $x_n$

$$x_n \propto \bar{d} T_e + \Delta d \int_{(n-1)T_{read}}^{(n-1)T_{read} + T_e} p(t) \, dt \quad (4)$$

where $T_{read}$ and $T_e$ are, respectively, the readout and exposure time of the CMOS camera.
camera. Here, we assume that the CMOS camera starts capturing the image frame at time \( t = 0 \). From the expression in equation (4), we can see that due to the rolling shutter effect, the signal \( p(t) \) is encoded into the columns of the image. Note that the desired average dimming level \( \tilde{d} \) adds a bias to the intensity of the pixel.

In order to capture (and later decode) the modulating signal \( p(t) \) in the image frame of a CMOS camera,\(^{25}\) the exposure time \( T_e \) needs to be chosen such that \( T_e f_{T_x} < 1/2 \). Note that a faster exposure time \( T_e \) will result in sharper bright/dark strips. The readout time of the camera \( T_{\text{read}} \) determines the width of the captured strip. Since the readout time of the camera is a device-related constant, the width of the captured strips in the image does not change for a given transmitting frequency.\(^{24}\)

In Figure 5, we show an example of how the modulating signal \( p(t) \) is captured as bright and dark strips by the rolling shutter CMOS camera. The orange dashed line in Figure 5 corresponds to one image column that is exposed to light when the luminaire has a higher light output, while the blue dashed line shows that another column is exposed to light when the luminaire has a lower light output.

In Figure 6, we show captured images of an LED luminaire with two exposure modes and a transmitting frequency of 1500 Hz. The top image is captured using auto exposure mode \((T_e = 1/140 \text{ s})\), while the bottom one is captured using a manual exposure mode \((T_e = 1/8000 \text{ s})\). The modulating signal can only be detected using manual exposure mode when the image is underexposed. Note that only the bright and dark strips shown along the columns of the image correspond to the modulated signal. The stripes along the rows as shown in the bottom image of Figure 6 are the gaps between LED tubes (four in total in this example) and reflections within the fixture of the luminaire.

### 3.3. Smartphone demodulation

To demodulate the signal from the captured image, a luminaire detection method is
applied to find the region where each of the individual luminaires appears in the image. The luminaire detection method is based on the detection method proposed in Kuo et al., to extend it to more general non-circular (e.g. rectangular) shaped luminaires (step 4 below).

The luminaire detection steps are summarized as follows:

1. Convert the image to grey scale.
2. Blur the image to smooth the LED tubes and the fixture.
3. Apply a binary OTSU filter to separate the LED luminaires from the background image.
4. Label the LED luminaires and determine the boundary of the LED luminaires in the image. Each luminaire region is labelled as a connected component in the binary image, following the approach in Haraloc and Shapiro. The luminaire boundary is determined as the smallest rectangular area that fully contains the connected component.

In Figure 7, we show an example of the luminaire detection method applied to two LED luminaires contained in an image captured by a user.

After the luminaire has been detected, we proceed to determine its transmitting frequency, i.e. its identifier. The proposed processing stages are as follows:

1. The first step of image processing is to apply blurring to the grey-scale image of the luminaire. The blurring reduces the noise and smooths the image of the fixture of the luminaire.
2. Note that the sequential exposure of the image is performed in a fixed dimension, i.e. columns of the image. The second step is to calculate the total intensity of each column of the image, i.e.

\[
x_q = \sum_{p=1}^{P} y_{p,q}, \quad q = 1, \ldots, Q
\]

where \(Q\) and \(P\) are, respectively, the number of columns and rows of the image, and \(y_{p,q}\) is the \((p, q)\)th pixel of the grey-scale image.

3. Next, we filter the DC component of equation (5) and apply the discrete Fourier transform (DFT) to the DC-filtered 1D signal \(\bar{x}_q\).

\[
\mathcal{F}(f) = \sum_{q=1}^{Q} \bar{x}_q e^{-2\pi j \left(\frac{(q-1)}{Q}\right)}, \quad f = 0, \ldots, Q - 1
\]

4. Finally, the estimated transmitting frequency can be obtained as in Lee et al.

\[
\tilde{f}_{Tx} = \frac{f^*}{Q T_{read}}
\]

where

\[
f^* = \arg \max_f \mathcal{F}(f)
\]

In Figure 8, we show an example of the frequency detection process for a LED luminaire with a transmitting frequency of 2100 Hz. We can see that a clear peak is detected at a frequency of 2100 Hz.

In Figure 9, we show the linear relationship between the normalized image frequency \(\tilde{f}\) and the luminaire transmitting frequency \(f_{Tx}\). This illustrates the luminaire transmitting frequency has a direct mapping to the corresponding normalized image frequency after application of the DFT.

3.4. Performance evaluation

We now evaluate how the proposed demodulation scheme performs in an experimental office lighting test bed (details of the test bed are described in Section 5). The
detection accuracy of our proposed demodulation scheme is determined as the percentage of successful detections of the transmitting frequency from the captured image set, with 50 images. A single luminaire was used, with all the other luminaires off. The estimated transmitting frequency $\tilde{f}_{TX}$ is classified as correct if it is within 50 Hz of the actual transmitting frequency $f_{TX}$, i.e. $|\tilde{f}_{TX} - f_{TX}| \leq 50$ Hz. The tests were performed using a Samsung S7 smartphone, with Android version 6.0.1.

As mentioned in Section 3.2, the exposure time $T_e$ affects the intensity of bright and dark strips. To ensure good detection performance under high dimming level and/or high transmitting frequency, a short exposure time is chosen. Film speed (ISO) determines camera sensitivity to light and thus also affects the intensity of the bright and dark strips. In this case, the ISO is set to a low value to maximize the contrast between strips. For the smartphone camera in use, the

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**Figure 7** Luminaire detection steps: (a) grey-scale image, (b) blurred grey-scale image, (c) binary OTSU filter and (d) LED luminaire boundary.
camera properties are $T_e = 1/8000$, ISO = 100 and $T_{\text{read}} = 65\mu$s.

First, we consider the effect of the luminaire orientation with respect to the scanning direction of the rolling shutter as given by angle $\theta$ (see Figure 10) in the detection accuracy of our proposed method. In Figure 11, we plot the detection accuracy for different ranges of orientation angle $\theta$: $[-10^\circ, 0^\circ, 10^\circ, \ldots, 80^\circ]$. For each range, 50 captured images were obtained. During this test, the average dimming level is set to $d = 0.5$ and the modulation depth is chosen as $\Delta d = 0.05$. In Figure 11, we see that the detection accuracy reduces as the orientation angle $\theta$ increases (the small increase in detection accuracy from $\theta = 30^\circ$ to $\theta = 40^\circ$ is attributed to the moderate size of the image dataset). When the orientation angle $\theta$ is close to $90^\circ$, the gap between the LED tubes is the
dominant part in the rectangular area of the luminaire instead of the bright and dark strips. In this situation, the summation in equation (5) does not reflect the transmitting frequency of the luminaire, but the frequency introduced from the gap between the LED tubes in the image.

Next, we considered the impact of the following factors on the frequency detection accuracy: (1) luminaire dimming level, (2) environment illumination and (3) luminaire transmitting frequency. During the experiments, only one factor is varied, while fixing the other two factors, to determine its influence on the detection performance of the proposed method.

*Dimming level:* During this test, the transmitting frequency is set to 2100 Hz under the absence of daylight. The average dimming...
level $\tilde{d}$ of the luminaire is varied from 0.1 to 1.0 with steps of 0.1. The modulation depth is chosen as $\Delta d = 0.05$. In Figure 12, we show the performance of our proposed method. In general, the detection accuracy decreases when the dimming level increases. This is because a higher average dimming level $\tilde{d}$ emphasizes the luminaire fixture introducing errors in the frequency of detection.

*Environment illumination:* In this test, the transmitting frequency is set to 2100 Hz, but this time, daylight (230 lx) is introduced. The average dimming level $\tilde{d}$ of the luminaire is varied from 0.1 to 1.0 with steps of 0.1. The modulation depth is chosen as $\Delta d = 0.05$. Compared with the first experimental test, it was found that the additional illumination introduced by daylight adds an additional bias to the pixel intensities. Figure 13 shows the effect of daylight (230 lx) on the detection accuracy performance. Compared with the case without daylight, it can be seen the overall performance decreases by a few percentage points.

*Transmitting frequency:* To determine the impact of transmitting frequency on demodulation performance, a transmitting frequency ranging from 1500 Hz to 4200 Hz was chosen. During this test, the average dimming level was set to $\tilde{d} = 0.5$ and the modulation depth was chosen as $\Delta d = 0.05$. The test was performed in the absence of daylight. Figure 14 shows the detection accuracy performance under different transmitting frequencies. It can be seen that detection accuracy is higher than 90%.

4. Lighting control algorithm

In Section 4.1, we describe briefly the state-of-the-art lighting control system. In Section 4.2, we present our proposed lighting control system, as illustrated in Figure 15, with the human-in-the-loop component.

4.1. State-of-the-art lighting control system

The goal of the state-of-the-art lighting control system is to achieve target illumination levels at the light sensors located at the ceiling while maintaining a minimum illumination level at such light sensors. Let $d^{(k)}$ be the dimming level vector containing the dimming levels of the LED luminaires in the lighting system at iteration $k$. The dimming level describes the intensity of light output of an LED luminaire and takes a value between 0 (off) and 1 (fully on).

![Graph showing impact of daylight (230 lx) on detection accuracy]

*Figure 13* Impact of daylight (230 lx) on detection accuracy

*Lighting Res. Technol. 2017; 0: 1–21*
The behaviour of the state-of-the-art lighting control system can be formulated as an optimization problem. The desired dimming level vector $d^{(k)}$ at iteration $k$ of the lighting system is obtained as

$$d^{(k)} = d^{(k-1)} + \Delta d^{(k)}$$

$$\Delta d^{(k)} = \max(-\delta d, \min(\delta d, \eta(d^{\star(k)} - d^{(k-1)}))$$

where $\mathbf{1}$ is a vector of ones, with the minimum and maximum operations being done component-wise. The parameter $\Delta d^{(k)}$ is the...
adjustment step in dimming levels at iteration \( k \). \( \delta_d \) determines the maximum change of dimming levels between iterations, and \( 0 \leq \eta \leq 1 \) is a smoothing factor. The target dimming vector \( d^{* (k)} \) is obtained as the solution to

\[
d^{* (k)} = \arg \min_d \| Ad + s^{(k-1)} - l^{* (k-1)} \|^2
\]

subject to

\[
\begin{align*}
\sum_n A_{m,n} d_n + s^{(k-1)}_m & \geq l^{* (k-1)}_m \quad \forall m \\
0 \leq d_m & \leq 1 \quad \forall m
\end{align*}
\]

where \( s^{(k)}_m \) is the daylight contribution at light sensor \( m \) at iteration \( k \). In practice, an estimate of the daylight contribution at iteration \( k \) may be calculated using the light sensor values \( l^{* (k)}_m \) and dimming levels \( d^{(k)}_m \) at iteration \( k \) as

\[
s^{(k)}_m \approx l^{(k)}_m - \sum_n A_{m,n} d^{(k)}_n
\]

(10)

Note that equation (10) is valid as daylight changes slowly between iterations.

The target reference set points \( l^{* (k)}_m \) at iteration \( k \) are calculated as given by equation (2). The first inequality constraint of equation (9) indicates that the combined illumination from artificial light and daylight is above the target reference set point. The second inequality indicates the physical dimming constraints of the luminaire.

4.2. Proposed lighting control system

As described in Section 2, the state-of-the-art lighting control system does not take into account user preferences while controlling the illumination. Our proposed lighting control system is designed to satisfy illumination requirements at light sensors at the ceiling as well as user preferences.

Via a smartphone the user provides the following information at each iteration \( k \): (1) Set of neighbouring luminaires: Using the method described in Section 3, the smartphone detects the transmitting frequencies (i.e. IDs) of all luminaires within the neighbourhood of its current workplace \( r \), i.e. the set of luminaires \( \mathcal{N}_r \).

(2) Average image pixel value: The average pixel value \( \omega^{(k)}_r \) of the captured grey-scale image at workplace \( r \) during current iteration \( k \) is computed as \( \omega^{(k)}_r = \frac{1}{pQ} \sum_{p,q} y_{p,q} \). Note that the average pixel value is an indicator of the illumination level at the workplace. When the illumination level at the workplace increases (or decreases), then the average pixel value also increases (or decreases).

(3) Illumination preferences: The user is limited to maintain or increment/decrement by a factor \( \beta \) the current illumination levels at that particular location \( r \).

Using the information provided by the user, the lighting control algorithm works as follows

\[
d^{(k)} = d^{(k-1)} + \Delta d^{(k)}
\]

\[
\Delta d^{(k)} = \max(-\delta_d 1, \min(\delta_d 1, \eta (d^{* (k)} - d^{(k-1)})))
\]

\[
d^{* (k)} = \arg \min_d \| Ad + s^{(k-1)} - l^{* (k-1)} \|^2
\]

subject to

\[
\begin{align*}
\sum_n A_{m,n} d_n + s^{(k-1)}_m & \geq l^{* (k-1)}_m \quad \forall m \\
0 \leq d_m & \leq 1 \quad \forall m
\end{align*}
\]

(12)

and \( \tilde{l}^{(k)}_m \) is the new user-modified target reference set point at iteration \( k \) for light sensor \( m \).

The user-modified target reference set point \( l^{(k)}_m \) at iteration \( k \) is given by

\[
\tilde{l}^{(k)}_m = \min(s^{(k)}_m + c^*_m, \alpha^{(k)}_m l^{p}_m)
\]

(13)
In order to ensure feasibility of optimization problem in equation (12), the new user-modified target reference set points cannot exceed the combined value of current daylight light level \( s_m^{(k)} \) and the maximum contribution of artificial light \( e_m^* \), i.e. \( \tilde{s}_m^{(k)} \leq s_m^{(k)} + e_m^* \).

The parameter \( \alpha_m^{(k)} \) is a scaling factor applied to the target reference set point \( h_m^{(k)} \) given by

\[
\alpha_m^{(k)} = \begin{cases} 
\alpha_m^{(k)}, & \text{if } |\Delta d_m^{(k)}| \leq \epsilon_d \\
\alpha_m^{(k-1)}, & \text{otherwise}
\end{cases}
\]

(14)

Note that the scaling factor is only updated when the lighting control algorithm has converged, i.e. \( |\Delta d_m^{(k)}| \leq \epsilon_d \) where \( \epsilon_d \) is a dead band.

By default, the scaling factor is set to 1. In this case, the proposed and the state-of-the-art lighting control system have the same behaviour. However, when the user requests an increment or decrement of illumination levels, the scaling factor is modified as follows. A new scaling factor \( \alpha_m^{\text{new}(k)} \) is determined by

\[
\alpha_m^{\text{new}(k)} = \max \left\{ \alpha_{\min}, \min \left\{ \alpha_{\max}, \alpha_m^{(k-1)} + \sum_r \delta_{m,r}^{(k-1)} \right\} \right\}
\]

(15)

where \( \alpha_{\min} \) and \( \alpha_{\max} \) are, respectively, lower and upper limits. Here, the parameter \( \delta_{m,r}^{(k)} \) is a factor change of luminaire \( m \) requested by workplace \( r \), given as

\[
\delta_{m,r}^{(k)} = \begin{cases} 
\frac{1}{P_m} \delta_{\text{step}}, & \text{if } \omega_r^{(k)} \leq \beta_r \omega_r^* - \Delta \text{ and } m \in \mathcal{N}_r \\
-\frac{1}{P_m} \delta_{\text{step}}, & \text{if } \omega_r^{(k)} \geq \beta_r \omega_r^* + \Delta \text{ and } m \in \mathcal{N}_r \\
0, & \text{otherwise}
\end{cases}
\]

(16)

where \( \omega_r^* \) is the measured average pixel of user at workplace \( r \) when the user determines to increase/reduce the illumination. This is set as a starting point of illumination for lighting control. The scaling factor \( \beta_r \) is chosen depending on the request from the user. If the user desires to increase the illumination, \( \beta_r \) is greater than 1, otherwise, it is smaller than 1. Here, \( P_m \) is the number of users that have luminaire \( m \) within its neighbouring set of luminaires. Parameter \( \delta_{\text{step}} \) is a step change.

5. Experimental results

In this section, we focus on the performance evaluation of the proposed lighting control system. The proposed lighting system was implemented in an experimental office test bed with \( N = 8 \) luminaires placed at the ceiling in a \( 2 \times 4 \) grid as depicted in Figure 16. Each luminaire has a unique identifier and has a co-located light sensor and an occupancy sensor. The VLC frequencies of the luminaires range from 1500 Hz to 3600 Hz with a uniform frequency separation of 300 Hz.

The area under each of the luminaires corresponds to a zone, which may correspond to a workplace. The indexing of each zone is the same as the luminaire above it as depicted in Figure 16. A snapshot of the office space with an indication of zone 1 is depicted in Figure 17. There are two windows on the north side of the office with blinds that can be used to control the amount of daylight across the zones. The height of the office ceiling is 3 m, while the distance between the top of the desks and the ceiling is 2.1 m approximately.

All the luminaires and sensors in use were connected to a central controller via data acquisition (DAQ) hardware. The DAQ provides the read-in of the sensor values and the readout of the luminaires’ dimming levels. The central controller was run on a computer. The central controller processed the received smartphone images to obtain information about the luminaire identifiers and current
workplace illumination. The communication between the user’s smartphone and the central controller was implemented via the internet.

The following control parameters were set in the experiments: $W_{ave} = 610$ lx is the measured average illumination of the office space when all luminaires are switched on at maximum light output. We shall assume that the preference level of users is 500 lx and is the same level that the lighting control system
seeks to achieve at the workplace level under occupancy. The parameters for adapting dimming level as given in equation (11) are $\delta_d = 0.05$ and $\eta = 0.1$. The dead band for adapting dimming level is set as $\epsilon_d = 0.1$. The upper and lower limits of the calibration factor are $\alpha_{\min} = 0$ and $\alpha_{\max} = 2$. In equation (14), $\beta_p = 1.5$ is chosen for increasing the illumination and $\beta_p = 0.7$ is chosen for decreasing the illumination, while the step change of the calibration factor is $\delta_{\text{step}} = 0.05$.

To evaluate the performance of the proposed system, we consider the achieved illuminance at the workplace level and at the ceiling light sensors as well as the dimming levels of the luminaires under two scenarios with changing occupancy and daylight. For each scenario, the behaviour of the proposed system (Section 2.2) is compared with that of the reference approach (Section 2.1).

**Scenario 1**: In this scenario, the workplace in zone 1 is occupied by a user. We assume that the desired illumination of the user in zone 1 is around 500 lx. The user reports luminaires 1, 2 and 3 for control access to the central controller. During the first 30 s ($0 \leq t < 30$ s), the office is unoccupied and daylight is absent (both blinds are rolled down). At $t = 30$ s, zone 1 becomes occupied. It can be seen from Figure 18 that, without daylight, the illumination provided by the system at the workplace is around 450 lx in a stable state ($t = 80$ s). During the calibration phase, the target reference set point is set by the average illumination over the zones. Since zone 1 is at the corner of the office, this value results in a lower desired illumination. For the proposed system, the user is able to increase the illumination at the workplace. It can be seen that at $t = 100$ s, the illumination has increased to 500 lx as desired by the user. It can be seen from Figure 19 that the dimming levels of luminaires 2 and 3 within the workplace are increased to respond to the requirement of more illumination. Luminaire 1 is unable to provide more illumination because it has already reached its maximum dimming level output. At the 250 s mark, daylight enters the office (blinds are rolled up). For the reference lighting control system, the provided illumination at the workplace goes down to around 350 lx, causing under-illumination at the workplace. As mentioned in Section 1, this happens because in some cases the mapping of the illumination contribution at the workplace provided by the artificial light can be different from that of the combination of artificial light and daylight.
As for the proposed lighting control system, when the user perceives under-illumination, user control is applied to the system again, thus increasing the illumination at the workplace back to 500 lx. Again, in Figure 19, luminaires 2 and 3 are dimmed up to illuminate the workplace. At \( t = 480 \) s, zone 1 is unoccupied and blinds are rolled down and the experiment ends at the 600 s mark.

**Scenario 2:** In this scenario, zones 1 and 8 are occupied during the experiment. The user in zone 8 is satisfied with the illumination and does not adapt the illumination. In comparison, the user in zone 1 adapts the illumination according to his/her preferences (around 500 lx). Note that any changes in zone 1 have little effect in zone 8 and therefore we only show the behaviour of luminaires and illumination levels at zone 1. During the first 30 s \((0 \leq t < 30)\), the office is unoccupied and without daylight (blinds are rolled down). At \( t = 30 \) s, zone 8 becomes occupied. At this moment, zone 1 is still unoccupied and has an illuminance of around 250 lx, as shown in Figure 20. At \( t = 120 \) s, zone 1 also becomes occupied by another user. The illumination provided by the system is around 450 lx. The user in zone 1 is not satisfied with the illumination at its workplace and wants to increase the illumination level. The user in zone 1 starts to control the illumination level at its zone at around \( t = 180 \) s. The reported luminaires to control are luminaires 1, 2 and 3. Figure 21 illustrates that the dimming levels of luminaires 2 and 3 are increased to respond to the user’s illumination requirement. At \( t = 240 \) s, the illumination meets the user’s preference, and the illuminance at the workplace reaches 500 lx. At the 300 s mark, daylight enters the office (blinds are rolled up). The reference system only provides 300 lx in zone 1, causing under-illumination at the workplace. The reason for under-illumination is the same as that given for Scenario 1. However, for the proposed system, the user has the ability to increase the illumination back to 500 lx again. At \( t = 540 \) s, the user in zone 8 leaves and zone 8 is unoccupied. The performance of the proposed system however remains stable with respect to the change in occupancy status. At \( t = 660 \) s, zone 1 is unoccupied and blinds are rolled down, and the experiment ends at the 720 s mark.

To summarize, compared with the reference lighting control system, the proposed lighting control system is able to maintain illumination levels as desired by a user. In the absence of daylight, the proposed lighting
control system is able to adjust the illumination when the reference set point of a luminaire does not precisely match the desired illumination at the workplace. When daylight comes into the office, the proposed lighting control system restores the illumination at the workplace when the mapping of the illumination contribution at the workplace is different from the calibration phase using artificial light. As a result, human-in-the-loop controls improve the performance with respect to the illumination at the workplace, providing the access of lighting control to the user to meet his/her personal preference.

6. Conclusions and discussions

We proposed a human-in-the-loop control enhancement to sensor-driven smart lighting systems. A user obtains VLC identifiers of luminaires in the vicinity to control and feeds
back average image pixel values to the controller to indicate whether more or less illumination is required. Experimental results in an office test bed indicated that the proposed solution alleviates the problem of workplace under-illumination that may occur in reference sensor-driven lighting control systems.

A proof-of-concept human-in-the-loop component was introduced in a sensor-driven lighting control system. Further work needs to be done on user interface aspects. Long-term usage of such systems that allow users to interact with lighting also needs further study. The effect of conflicts in personal control preferences among users has to be studied further. Approaches to deal with personal control preferences have been considered\(^{31}\) and may be applied to the proposed lighting control system; this is a topic of future investigation. As part of lighting in an office space over long periods of time, two specific effects impact illumination: lumen depreciation\(^{32}\) and movement of objects in the indoor space. The effects of luminaire degradation or furniture movement in the illumination performance have been considered in other studies.\(^{10,11}\) Note that because our proposed system considers user input and preferences with respect to the achieved illumination (in terms of the average pixel value), the achieved illumination levels would be quite close to user preferences. As such, the proposed system provides some robustness to such long-term lighting effects. It would also be interesting to investigate how the system may learn user preferences from long-term data related to user interactions with the system. Such data may be used in addition to sensor data from the lighting system\(^{33}\) to improve system performance.

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