# Conflict management in a personalized, space model based lighting control system

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**Abstract.** Modern people spend most of their time indoors. In office buildings, in particular, it is important to achieve adequate lighting conditions supporting productive work. Studies suggest that personal lighting control improves user satisfaction and energy efficiency. We have developed a lighting control system that uses a space model to facilitate lighting personalization. However, our system currently does not address conflicts that may arise when multiple users share luminaires. In this paper, we describe how lighting control agents, supported by the space model, might manage these conflicts. A working prototype and results of preliminary tests are presented.

## 1. Introduction

Modern people spend most of their time indoors. In office buildings, in particular, it is important to achieve adequate lighting conditions supporting productive work. Studies suggest that personal lighting control improves user satisfaction and energy efficiency (Newsham et al. 2009).

We have developed a lighting control system in which lighting control agents manage lighting on behalf of users (Suter et al. 2012). Agents query a space model to retrieve luminaires that are near a user location. They adjust the states of luminaires based on user preferences. However, our system currently does not address conflicts that may arise when multiple users share luminaires. In this paper, we describe how lighting control agents, supported by the space model, might manage these conflicts.

The paper is organised as follows. In Section 2, we review related work in the areas of lighting automation systems and context-aware computing. In Section 3, we describe the lighting control system which we have developed. In Section 4, we describe how conflict management works in our system. Results of preliminary tests are presented in Section 5. We conclude with ideas for future research in Section 6.

## 2. Related work

### 2.1 Personalized lighting control

There are commercial systems that allow users to personalize lighting conditions (see, for example, Lutron (2013), Philips (2013), Zumtobel (2013)). In these systems, lighting objects such as luminaires or shades are aggregated into control groups that are adjusted together. This reduces commissioning costs, but control is typically too coarse grained. Alternatively, each lighting object may be adjusted individually by users. However, this may be tedious when output of several lighting objects need to be adjusted individually. Common to these systems is that they lack adequate management of conflicts that may arise when multiple users share lighting objects. Krioukov et al. (2011) designed and implemented a shared virtual light switch. In this system, users simply override the previous state. Wen & Agogino (2011) formulate lighting actuation as a linear programming problem to find optimal light outputs for luminaires. This approach may not be sufficiently flexible as it just considers illuminance levels and requires accurate information about surface reflection and luminaire photometric distribution to simulate illuminance levels at user locations. Mahdavi (2008) introduces a simulation assisted lighting control system. In this system, spatial relations between light objects and workplaces must be manually hard-coded into the controller. Fischer et al. (2012) propose a lighting control system that uses a transfer matrix generated by lighting simulations and Matlab.

### 2.2 Conflict management in context-aware computing

Existing work in context-aware computing is relevant for conflict management in personalized lighting control systems. Shin & Woo (2009) propose a service conflict management framework for detecting and resolving conflicts of multiple users who share context-aware applications in a smart home. They offer resolution strategies based on preferences and priorities. In case of lighting, they deal only with a single luminaire. Huerta-Canepa & Lee (2008) resolve conflicts using temporal ownership. Park et al. (2005) propose a dynamic conflict resolution scheme that minimizes the amount of dissatisfaction of all users involved in conflicts based on user preferences. Thyagaraju et al. (2008) apply a role and priority based conflict resolution method to control a television set.

## 3. Our personalized, space model based lighting control system

### 3.1 System architecture

In our previous research, we have developed a personalized lighting control system that provides lighting for individual users based on their location and lighting preferences (Suter et al. 2012). The system currently only addresses artificial lighting. Luminaires that are near a user location are dynamically derived from a space model. The system architecture is shown in Figure 1. On the client side, the main module is the Personal Lighting Manager (PLM), which reads illuminance and symbolic location data from, respectively, Illuminance Sensor (IS) and Near Field Communication (NFC) modules. These modules run on a user's smartphone. Both IS and NFC generate events when there are changes in illuminance levels or location. PLM receives these events, interprets them and, if necessary, sends sensor data together with the user's lighting preferences to the Lighting Control Agent (LCA) module. Preferences include a target illuminance level, an illuminance tolerance, and the size of the region covered by LCA. The latter is relevant in larger office spaces, where a user may need to control only a subset of luminaires. LCA retrieves luminaires that are near a user location from a space model that resides on the space model server (SMS). LCA then maps user preferences into luminaire outputs, which are actuated via a lighting automation system (LAS).

### 3.2 Space model server (SMS)

The space model stored on SMS consists of a network-based space layout (Suter 2010*a*,*b*) that includes lighting-specific elements. Desks and luminaires are modeled in addition to whole spaces (rooms) and subspaces. Figure 2 shows the lighting layout of a floor of an existing office building in Vienna where our test space is located. Desks and luminaires have subspaces whose

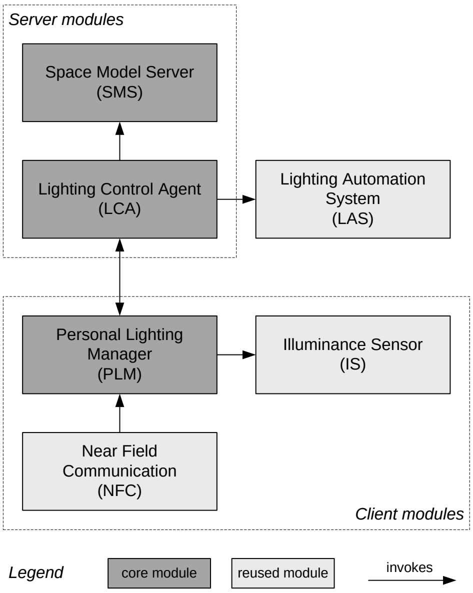


Figure 1: System architecture of the personalized, space model based lighting control system.

volumes are not shown in the figure to improve visualization. Windows are modeled because we plan to extend the system to address natural lighting and shading. Figure 2 further includes the proximity relation between subspaces and, respectively, desks and luminaires as well as the adjacency relation to subspaces. Both relations are modeled explicitly. Together with layout elements, they form a layout element network that is traversed to retrieve luminaires that are near a user location. Spatial relations are derived automatically from layout element geometries, which minimizes modeling errors and facilitates model maintenance. The corner office is our test space and enlarged in Figure 2. This office includes five desks and six luminaires that are arranged in an irregular 2x3 grid.

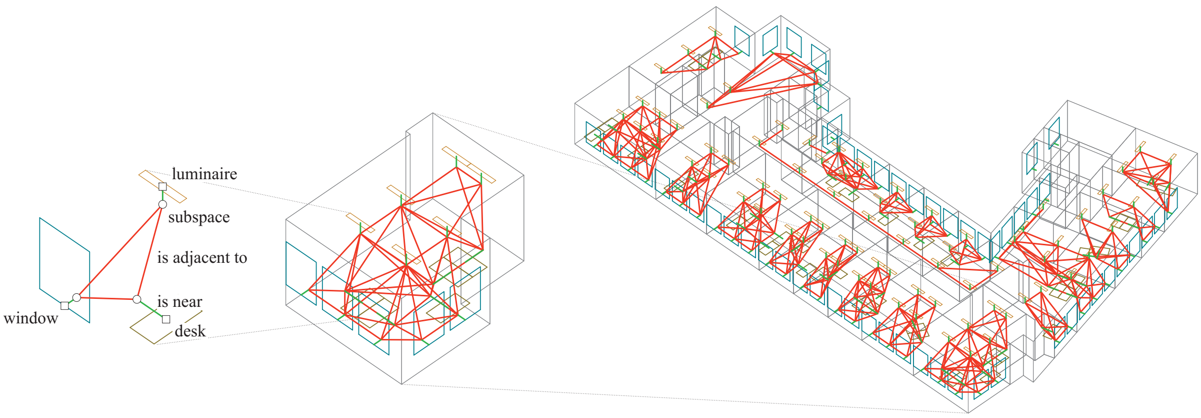


Figure 2: Lighting layout.

The query used to retrieve a set of luminaires operates on the lighting layout. Processing of the *GetLuminaires* query is done in four steps:

1. The lighting layout is searched for the element with the given identifier.

2. The retrieved element is the start vertex for searching the layout element network for the nearest luminaire. Edge length, that is, the Euclidean distance between vertices connected by an edge, is used as distance measure.

3. With the nearest luminaire as a start vertex, the network is searched for the set of luminaires that are in the range specified by the user. Number of edges in a path is used as distance measure.

4. Retrieved luminaires are weighted according to their distance to the luminaire that is nearest to the user location.

Distance weights computed in the last step are used by LCA to determine luminaire outputs, as is described next.

### 3.3 Lighting control agent (LCA)

Each luminaire obtained by LCA from SMS includes its distance relative to the luminaire that is nearest to the user location. LCA calculates luminaire outputs based on that distance. Luminaires that are near the user location have higher output than distant ones. The maximum distance (that is, the range of the region covered by LCA) is defined by user preferences.

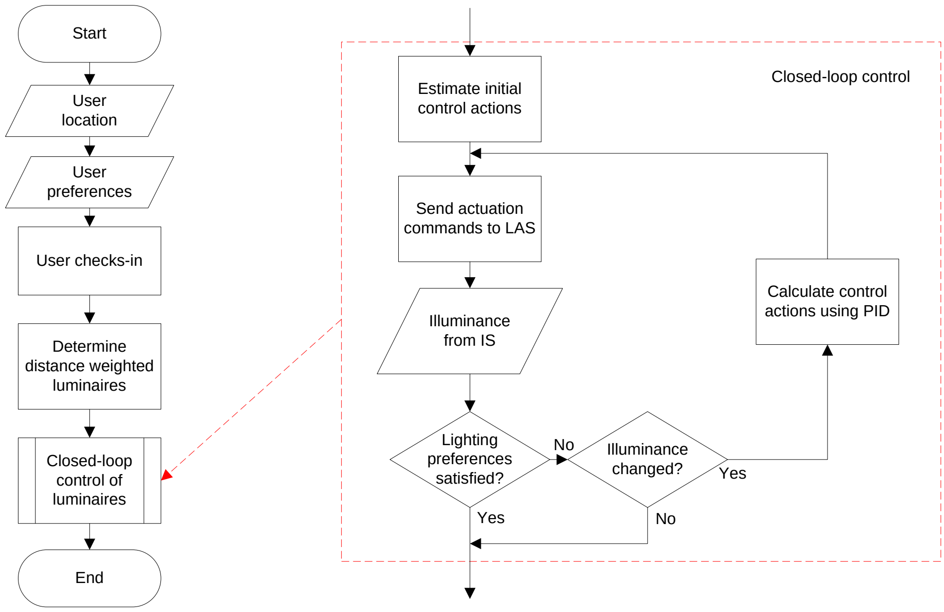


Figure 3: Single-user lighting control algorithm.

Luminaire outputs are adjusted by LCA based on closed-loop control that uses illuminance data measured by the user's smartphone for feedback (Figure 3). LCA actuates a first estimate of luminaire outputs via LAS. Subsequently, LCA iteratively adjusts luminaire outputs until measured illuminance at the user location is in the target illuminance interval defined by user preferences. In order to minimize overshoot and oscillation, a simple proportional-integral-derivative (PID) control loop is used (Aström & Murray 2010):

$$u_l(t) = F(d_l) * pid(t) \quad (1)$$

$$F(d_l) = 1 - C\frac{d_l}{R} \quad (2)$$

$$pid(t) = K_p(e(t) + K_i\int_0^t e(\tau)d\tau + K_d\frac{d}{dt}e(t)) \quad (3)$$

$$e = E_T - E_C \quad (4)$$

where: $u_l$ is the output for luminaire $l$, $F$ is a fade out function, $C$ is the fade out coefficient, $d_l$ is the distance between luminaire $l$ and the user, $R$ is the user-defined range preference, $E_T$ is the user-defined target illuminance, $E_C$ is the current illuminance, $e$ is the error, $K_p$ is the proportional gain, $K_i$ is the integral gain, and $K_d$ is the derivative gain.

According to the fade out function $F$, luminaires that are more distant to the user location have lower outputs than closer ones.

## 4. Conflict management

### 4.1 Overview

Certain luminaires may be shared when several users are present in a room. A conflict occurs if a shared luminaire has different preferred outputs. Our approach to conflict management is based on single-user control (Section 3.3).

The proposed conflict management alorithm addresses the scenario of a user checking into a desk when other users are already present. The latter should notice only minimal changes in luminaire outputs, and changes in outputs of non-shared luminaires are preferred. Also, no data should be collected from existing users to minimize data communication and ensure shorter response times. With modifications, the algorithm is applicable to other scenarios, such as users changing preferences, users checking out, or users relocating to another desk. For space reasons, these modifications are not described here. While our algorithm is extensible, it is not guaranteed to always find a solution that meets the preferences of all users, nor does it find an optimal solution.

The conflict management algorithm is shown in Figure 4. An LCA is instantiated for each room and responsible for lighting control in that room. It maintains a model of that room that includes anonymous user preferences, user location and luminaire data. The model is updated when a new user checks into a desk by querying the space model. LCA determines the set of luminaires that are near the user location. Next, it determines if any of these luminaires are shared with other users. A luminaire is shared with existing users if it is included in at least one set of luminaires that are near an existing user. This is illustrated in Figure 5. Luminaires in set $\{L2, L3, L4, L5, L6\}$ are near desk $D5$, where user $U2$ has checked in. Since luminaires in set $\{L1, L2, L3\}$ are near user $U1$, luminaires $L2$ and $L3$ are shared between $U2$ and $U1$. If there are no shared luminaires, then LCA adjusts outputs of these luminaires by single-user control. Effects of these adjustments on lighting conditions for existing users are considered as negligible. If there are shared luminaires, the algorithm first tries to satisfy lighting preferences of the new user with non-shared luminaires only. This reduces disturbances of existing users. If this is insufficient, outputs of luminaires that are shared between the new user and existing users are adjusted next. This is at first done with respect to the new user's preferences. Once known, the new user's preferred outputs of shared luminaires are subsequently reconciled with those of existing users by applying a conflict resolution method. Preferred outputs of existing users correspond to outputs prior to modifications for the new user.

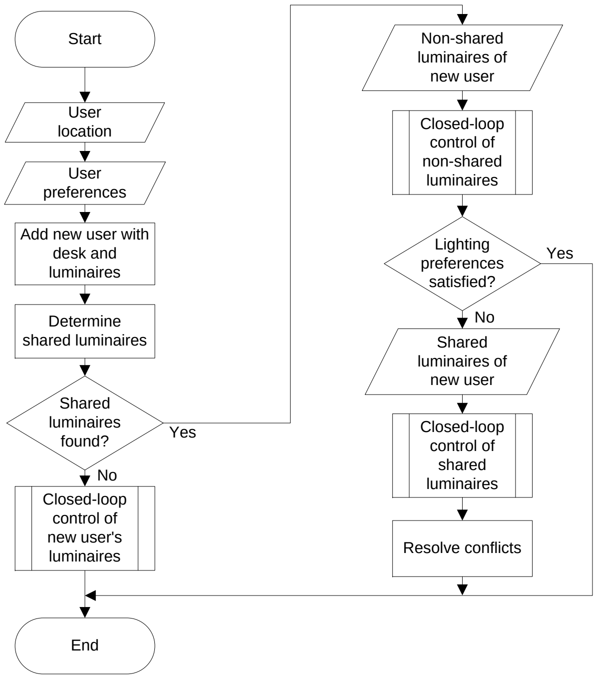


Figure 4: Conflict management algorithm.

### 4.2 Conflict resolution

Differences in preferred outputs of shared luminaires between the new user, on the one hand, and existing users, on the other hand, constitute conflicts that are resolved by LCA based on a conflict resolution method. A simple method would be to compute the average of preferred outputs of a shared luminaire. However, this may not be fair for users who are closer to a luminaire than others. Since LCA knows the distance of a luminare from each user, it can consider these distances for conflict resolution. That is, the preferred output of a user who is close to a luminaire has greater weight than that of a remote user:

$$u_l = \sum_{k=1}^{N} \left(M_k\left(d_l\right) * u_{lk}\right) \tag{5}$$

$$M_k\left(d_l\right) = \frac{F_k^2(d_l)}{\sum_{j=1}^{N} F_j(d_l)} \tag{6}$$

where: $u_l$ is the resolved output of luminaire $l$, $u_{lk}$ is the preferred output of luminaire $l$ of user $k$, $N$ is the number of users sharing luminaire $l$, and $M_k$ is the weighted multi-user fade out function for user $k$.

For example, in Figure 5, the distance of $L3$ from $L1$ and $L6$, which are nearest to users $U1$ and $U2$, respectively, is 1 and 2 edges. Only subspace adjacency edges are counted when computing these distances. If LCA determines preferred outputs of 50% and 10% for, respectively, $U1$ and $U2$, then the actuated output for $L3$ would be 34% according to our conflict resolution method. This function may be modified such that other factors are taken into account, such as tolerance, time of arrival, priority etc.

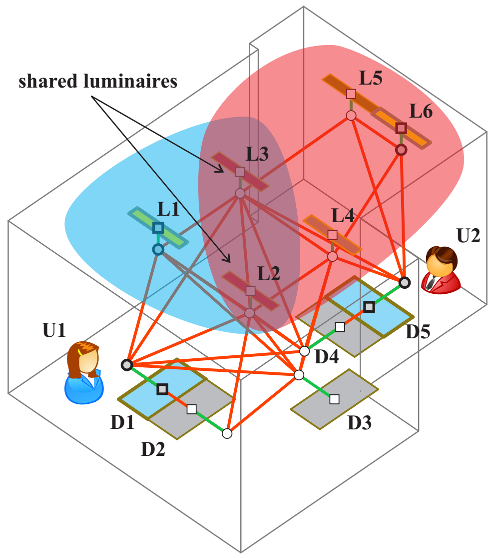


Figure 5: Determining shared luminaires.

## 5. Evaluation

We have extended an existing prototype of our personal lighting control system with the described conflict management capabilities. We have deployed the system prototype in a 35 m2 team office space featuring five desks, six luminaires, and five windows. We retrofitted the existing lighting system in the space with an LAS consisting of a Luxmate BMS to DALI gateway, an LM-SI03 serial interface, and DALI ballasts (Luxmate 2001, DALI-AG 2001). LCA communication with LAS is implemented in Python (Python 2013). We installed the PLM application on a Google Nexus S and two Samsung Galaxy S smartphones featuring the same type of illuminance sensor (Sharp 2013). The PLM module is implemented as an Android application. Communication between PLM, LCA, and SMS is done via Google Protocol buffers (Google 2008). LCA and SMS are implemented as Windows applications.

We are currently performing test cases to evaluate the effectiveness of conflict management of the system prototype. As evaluation metric we use average user satisfaction, which ranges from 0% (lighting preferences of no users are satisfied) to 100% (lighting preferences of all users are satisfied). For simplicity, individual user satisfaction is either 0% or 100%. Each test case is executed according to the following test plan. First, user $U1$ checks into a desk in the empty and unlit office space. The system tries to satisfy preferences of $U1$. After the check-in of $U1$ is completed, user $U2$ checks into another desk. The system performs conflict management to satisfy preferences of $U1$ and $U2$. Finally, user $U3$ checks into one of the remaining free desks. The system performs conflict management to satisfy preferences of $U1$, $U2$, and $U3$. No real participants are recruited yet for these preliminary tests. In order to generate different conflict management situations, we vary target illuminances, tolerances, and ranges preferred by $U1$, $U2$, and $U3$. Moreover, we let users check-in at different desks in the room.

Illuminance data sensed on smartphones are logged during test runs together with luminaire outputs. In order to evaluate the reliability and accuracy of smartphone sensors, illuminance data are logged independently at each user location with a professional luxmeter (Voltcraft 2008).

Preliminary test results will be presented in the full paper.

## 6. Conclusion

This paper described an extension of a personalized, space model based lighting control system with a method for managing conflicts in a multi-user scenario.

The conflict resolution algorithm may be augmented with resolution methods proposed in the literature. Automatic resolution may depend on factors such as priority over luminaires based on distance from the user, user presence duration, privileges, and so on (e.g. Shin & Woo (2009), Thyagaraju et al. (2008)). In our basic resolution method we already include distance between a user and a luminaire as a factor. Time elapsed since a user's check-in may be sensible to consider. For example, a user who works full time in an office may have higher priority than an occasional user. Similarly, special needs may justify giving privileges to users. For example, a visually impaired user may have higher priority than a regular user.

After completion of preliminary tests, we intend to run a user study with real participants in our test space. The scalability of the system in large open-plan offices will be evaluated in a discrete event simulation environment that emulates actions of larger user groups.

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