DESIGN OF A PERSONALIZED LIGHTING CONTROL SYSTEM ENABLED BY A SPACE MODEL

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ABSTRACT

This paper reports on a research effort to develop a prototype of a personalized lighting control system that adjusts the visual environment based on user preferences. Lighting controllers query a space model to retrieve lighting objects that are near given user locations and map user preferences into control actions for these lighting objects. A user scenario illustrates the concept of personalized lighting control. The scenario is used to develop functional and non-functional system requirements which inform system design. The structure of a proposed space model and space model queries are described and illustrated with examples. Implementation environments for system modules and data communication between modules are discussed. System and user tests are outlined that will be performed for initial feedback on the feasibility of personalized lighting control.

INTRODUCTION

Advances in building automation systems (BAS), building information modeling (BIM), and mobile computing have the potential to facilitate innovative building services that are more responsive to the needs of individual users. In the lighting domain, for example, lighting controllers are conceivable that manage visual environments on behalf of users. Control actions may be informed by user preferences, user locations, and models of spaces and lighting objects that surround users. This paper reports on an on-going research effort to design and implement such a personalized lighting control system.

There is empirical evidence of a correlation between indoor environment quality (IEQ) and user satisfaction, health, and productivity (Fisk 2000). In the lighting domain, studies suggest that individual dimming control of luminaires improves user satisfaction and, possibly, productivity (see, for example, Newsham et al. 2004).

Individual lighting control requires information about lighting objects, which include luminaires, openings, and shades, relative to a user location. In existing solutions, this information is typically hard-wired and/or hard-coded into the lighting control system. Lighting objects tend to be aggregated into static control groups in order to minimize system complexity and maintenance effort. This results in rather coarse-grained individual control. By contrast, a lighting controller with access to a space model may dynamically derive lighting objects that are near a given user location. It could choose control actions such that they optimize user preferences with respect to that particular context. A user of a personalized lighting control system may thus enjoy higher visual comfort while being largely relieved from managing the visual environment. Moreover, there would be no need to modify user or system settings when a user relocates, e.g. from one workplace to another. Compared with conventional systems, a personalized lighting control system may not only have higher user satisfaction, but may also improve energy effectiveness and reduce maintenance costs due to more fine-grained control and higher flexibility.

A user scenario is introduced in the next section to further illustrate the idea of personalized lighting control. Functional and non-functional system requirements are derived from the scenario, which involves artificial lighting control.

SYSTEM REQUIREMENTS

User scenario

Start situation: User N. enters his office at 7 a.m. on a winter day. Ceiling luminaires in the office are turned on to provide basic visual comfort. No other users are present yet in the office, where four workplaces are shared on a first-come-first-serve basis. A personalized lighting control application is installed on N.'s smartphone.

Flow of events: N. approaches an available workplace and puts his smartphone face up on the work desk. The smartphone detects N.'s location. The personalized lighting control application is triggered. The application uses N.'s location, his lighting preferences, and data from an illuminance sensor on the smartphone to adjust dimming levels of luminaires that surround N.'s desk. While the desk luminaire and ceiling luminaires that are near the desk are adjusted to high dimming levels, remote ceiling luminaires are adjusted to low levels as they have less influence on illumination of the work area. Dimming levels are set according to N.'s preferences for computer work, which is the assumed default activity. Desk illuminance is 495 lx, which is within N.'s preferred illuminance interval of 480 – 520 lx for computer work.

End situation: N. sets up his laptop and starts working. The visual environment corresponds to his preferences for computer work.

Functional requirements

Several functional requirements for a personalized lighting control system emerge from the scenario. First, a lighting controller is required which maps a user's lighting preferences into control actions that meet these preferences. As the scenario suggests, the lighting controller receives feedback from an illuminance sensor on the user's smartphone. This ensures that illuminance is measured near the user's work area.

Second, the scenario implies a space model that represents spaces, workplaces, and lighting objects. A space model query interface is required that lets lighting controllers retrieve lighting objects that are near a user location. The desired size of such a lighting zone may be specified by users. Some users may prefer large zones that include remote lighting objects, others small ones. According to the scenario, the lighting controller needs to know distances of desk and ceiling luminaires in the office relative to the user's desk. In natural lighting and shade control scenarios, similar information about windows and shades would be required. Dependent on the size of the space that contains a user location and the desired size of the lighting zone, all or a subset of lighting objects in the space are retrieved from the space model. A subset is sufficient e.g. in large open plan offices.

Third, the system needs access to symbolic indoor location data (Hightower and Borriello 2001, Lin and Lin 2005). In order to support the scenario, it is sufficient for the system to know that the user has arrived at a particular workplace. There is no need for continuous tracking of the user location, as required in certain indoor navigation applications. A smartphone could provide required symbolic location data, e.g. if it has the capability to detect known, nearby objects (such as tags or transmitters) via short range wireless networks.

For the proof of concept system prototype, which addresses artificial lighting control, the space model query interface is limited to the retrieval of luminaires. This simplified interface facilitates implementation. Each retrieved luminaire includes information about its proximity to the user location. An artificial lighting controller with basic functionality is feasible with this information.

When the user's smartphone fails to collect sensor data or suffers a power failure, then the system should fall back to non-personalized lighting mode.

Non-functional requirements

The system's response time to user actions is relevant for user acceptance. In the scenario, response time refers to the elapsed time between the user putting his smartphone on the desk and a modification of luminaire dimming levels that is noticeable by users.

Ideally, response time would be less than 0.1 seconds to make the user feel that the system is reacting immediately to his actions (Miller 1968). If the response time is between 0.1 and 1 second, then the user notices the delay. A response time of more than 1 second means that the system needs to communicate to the user, either via the smartphone or luminaires, that it is working on lighting adjustments.

The system must maintain specified response times during peak time periods (e.g. in the morning, after lunch), when many users are expected to arrive at their workplaces more or less at the same time. It must scale to large public or office buildings with hundreds of potential users.

The system must ensure user privacy. User preferences should be anonymous and not persistent in the system unless explicitly permitted by the user.

Non-requirements

The following aspects of personalized lighting control are relevant but beyond scope for the development of the proof of concept system prototype:

- multiple concurrent users sharing the same luminaires;
- natural lighting and shade control;
- consideration of glare and contrast factors based on user's pose and detailed geometric space models;
- multi-criteria lighting control optimization e.g. of visual comfort and energy efficiency; and
- consideration of system security, that is, protection of the system and its modules against unauthorized users.

However, awareness of these potential enhancements has influenced system design.

SYSTEM DESIGN

System architecture

A client/server architecture is proposed for a proof of concept prototype of a personalized lighting control system (Figure 1). Compared with a serviceoriented architecture, the benefit of a client/server architecture is its relative ease of implementation.

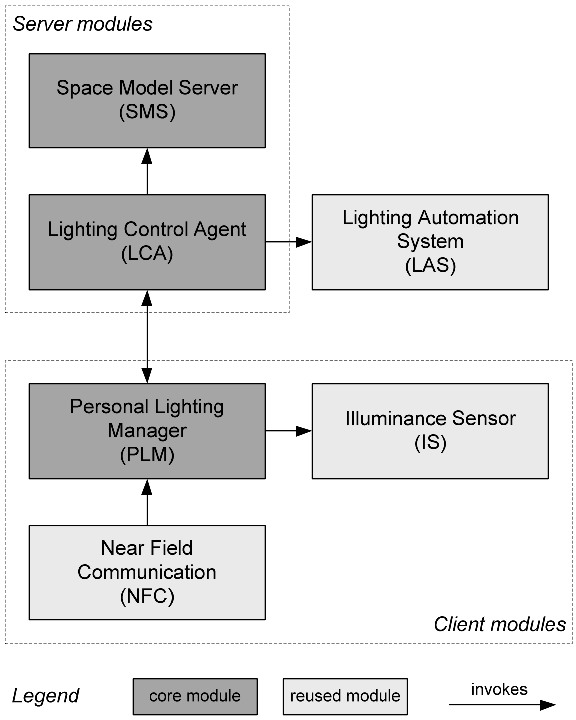

Figure 1. System architecture.

The system includes client and server modules. 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. NFC is chosen for symbolic location sensing because the technology is increasingly supported on smartphones (Juniper 2011).

Both IS and NFC process sensor data streams and generate events due to 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. IS discretizes illuminance sensor data in order to avoid overloading PLM. IS sends updates only when there are significant changes in lighting conditions. LCA is responsible for translating lighting requests into luminaire dimming actions. LCA interfaces with the lighting automation system (LAS) module, which executes these actions. LAS may be an existing lighting system that is enhanced with personalized lighting control functionality. LCA queries the space model server (SMS) module to obtain lighting objects relative to a user location. SMS has a space model that, among other things, includes information about spaces and related lighting objects in a building. The space model may also support space related information needs of other applications such as heating, ventilation, and air conditioning (HVAC), computer supported collaborative work (CSCW), or indoor navigation.

Sequence diagram

A sequence diagram illustrates the interaction between system modules (Figure 2). After the user has placed his smartphone near a tag that is mounted on the chosen desk, the tag is detected by the smartphone's NFC. PLM is alerted and determines that the user has arrived at the desk. It connects to LCA. A dedicated, asynchronous communication channel is established between PLM and LCA which is used for data exchange in both directions. PLM gets current illuminance data from IS and sends a lighting request to LCA. The request includes the user's lighting preferences, his current symbolic location, which is the id of the tag on his desk, and current illuminance data. LCA queries SMS to obtain luminaire objects relative to the user location. Each luminaire has a type and a weight attribute. The type attribute indicates if a luminaire is a desk or ceiling luminaire. The weight attribute encodes the distance (according to a distance measure) between the luminaire and the user location. LCA then retrieves the status of luminaires from LAS.

Three factors influence the computation of luminaire dimming levels:

1. Target illuminance interval on the user's desk according to user preference. For laptop work a user may specify a target illuminance of 450 - 550 lx.
2. Target ceiling to desk lighting ratio according to user preference. For laptop work a user may specify a target ratio of 40 % to 60 %.
3. Distance of ceiling luminaires to the user's desk.

Factors such as contrast or glare control are currently beyond scope because they require detailed information about geometric and non-geometric space scene and luminaire properties.

For the system prototype, LCA uses a simple closed-loop control algorithm. Initial dimming levels are estimated heuristically based on current illuminance (as measured by IS) and current luminaire dimming levels (as obtained from LAS). Near luminaires have higher dimming levels than remote ones because they have a greater impact on illuminance of the user's work area. Remote luminaires are primarily used for ambient lighting. Dimming requests are sent to LAS which actuates luminaires. PLM is notified by LCA when its lighting

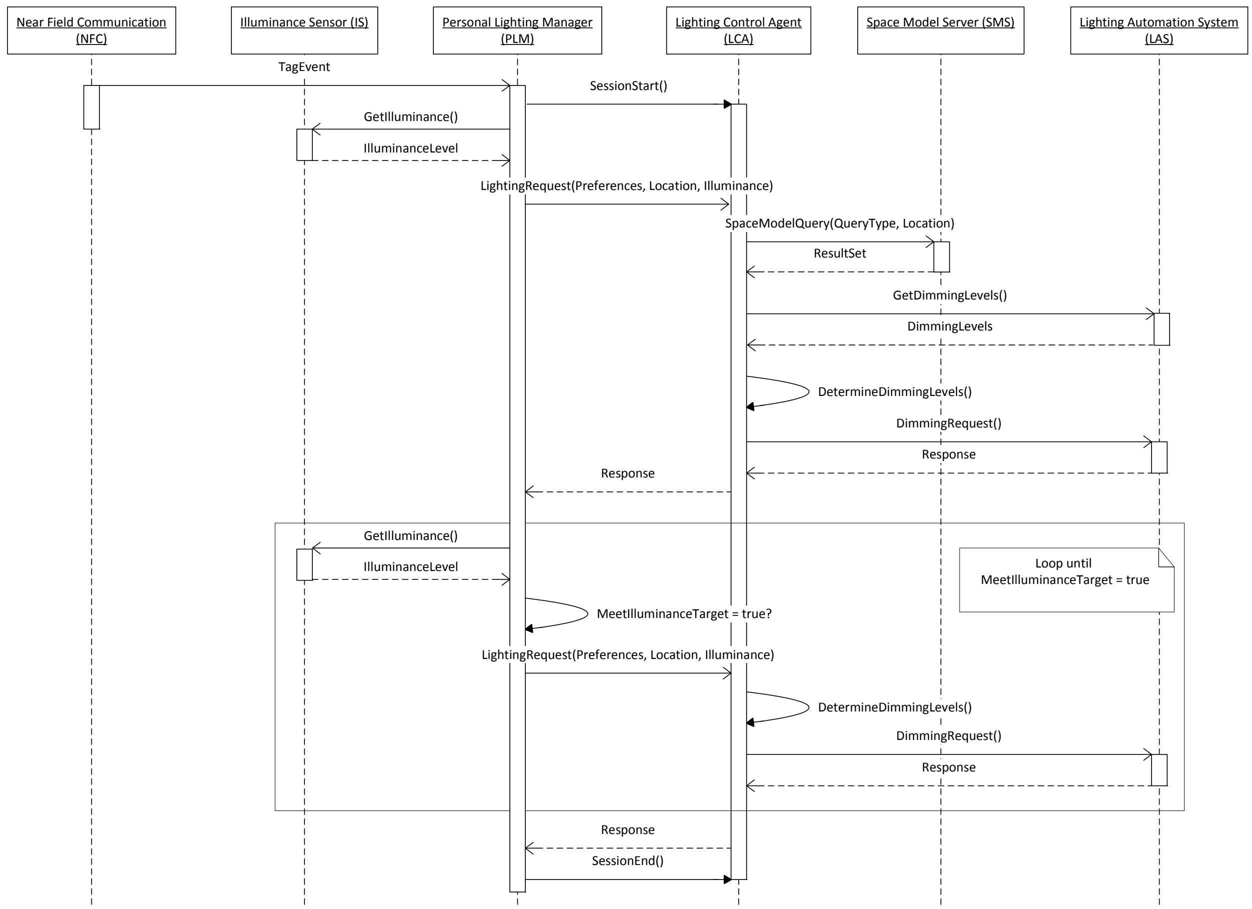

Figure 2. Sequence diagram of system module interactions for the scenario.

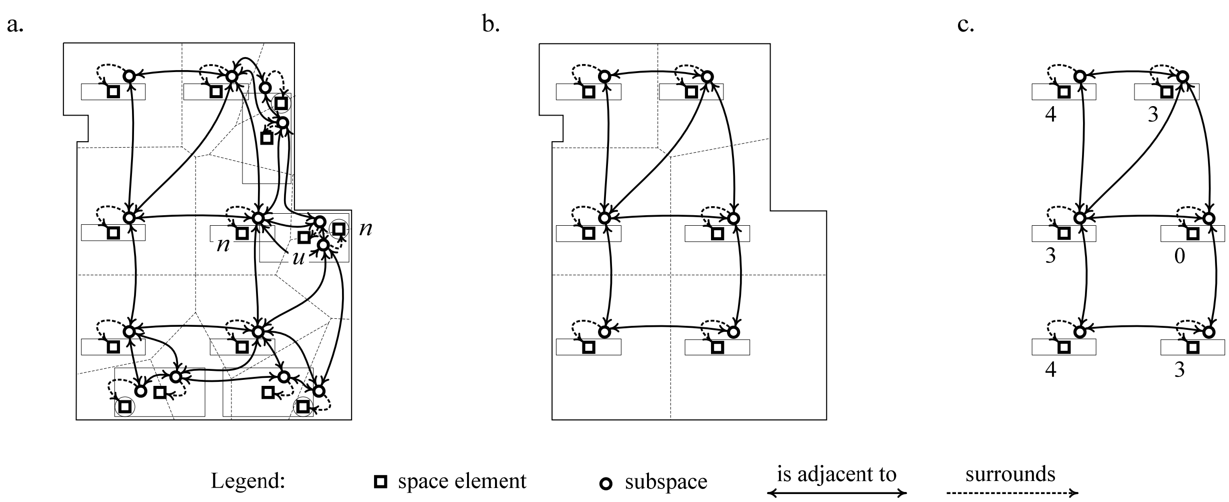

Figure 3. Layouts and networks of the test room. a. *Luminaire/Desk* layout, b. *Ceiling Luminaire* layout, c. *Ceiling Luminaire* network.

request has been fulfilled. PLM reads illuminance sensor data and checks if the measured illuminance is in the target illuminance interval. If so, then the session terminates and PLM waits for new events. If the target illuminance interval is not met, then PLM sends another lighting request to LCA. Since the same session is used and LCA keeps luminaire information, no SMS queries are necessary in subsequent control cycles. This minimizes query load on SMS. Dimming levels are incrementally increased or decreased until the measured illuminance is in the target illuminance interval.

SPACE MODEL

Space model structure

Spaces and related lighting objects in SMS are modeled based on a schema for network-based space layouts (Suter 2010a). The schema incorporates aspects of existing space models (see, for example, Bjoerk 1992, Eastman and Siabiris 1995, Ekholm 2000, BuildingSmart 2010). It adopts a space-centered (as opposed to an enclosure-centered) view. Concepts of network-based space layouts that are relevant in the context of this paper are briefly reviewed. For more detailed descriptions, the reader is referred to Suter (2010a) and Suter (2010b).

A space model consists of one or more layouts. A layout consists of four types of layout elements (*le*): whole spaces, subspaces, space boundary elements, and space elements. A whole space is a space which is bounded on all sides by space boundary elements. A space boundary element is part of an immaterial layer with zero thickness that bounds a whole space. A partial space or subspace is a space which is contained in a whole space. It may or may not be bounded on all sides by space boundary elements and may surround space elements. The latter are (physical) objects, including windows, tables, or luminaires that are either contained in or enclose a whole space. Space elements have attributes that indicate if they are whole space contained or whole space enclosing space elements (*cse* or *ese*). A desk is an example for a *cse*, a door for an *ese*. The distinction of *cse*s and *ese*s matters because they participate in different spatial relations.

The main data structure in a layout is a layout element network, which facilitates efficient queries with graph algorithms (Bondy and Murthy 2010). A layout element network is a directed, weighted graph with *le*s as nodes and spatial layout element relations (*ler*) as edges. *Le*s and *ler*s have weights. Spatial relations in an *le* network include certain adjacency, boundary, surrounds, and proximity relations between *le*s.

Two layouts of the test room for the planned system prototype are shown in Figure 3a and 3b. These layouts constitute the space model which is queried by LCA clients. Each layout features a single whole space. In general, layouts may include multiple whole spaces. For improved visualization, whole space and space boundary element nodes are not shown in Figure 3a and 3b. Similarly, the boundary relation between space boundary elements and, respectively, whole spaces and subspaces are not shown.

The whole space in the *Luminaire/Desk* layout (Figure 3a) contains desk luminaires, ceiling luminaires, and desks. By contrast, the whole space in the *Ceiling Luminaire* layout (Figure 3b) contains only ceiling luminaires. In both layouts, each space element (that is, luminaire or desk) is surrounded by a subspace, whose volumes are shown as dotted lines. Subspace volumes are geodesic Voronoi cells (Aurenhammer and Klein 2000). In order to derive geodesic Voronoi cells, subspace positions are used as sites, and whole space volume faces as obstacles. Each point in a geodesic Voronoi cell is, by the geodesic (that is, obstacle avoiding) distance measure, closer to the cell's site than to any other site. The subspace adjacency relation is derived from subspace volumes. Each space element has a space element type definition in which the positions of surrounding subspaces are defined.

Space model queries

LCA queries specific layouts in SMS to retrieve a set of luminaires that are near a given user location. Retrieved luminaires include desk and ceiling luminaires. A sequence of simple queries is combined into a single query request to avoid the exchange of intermediate query results between LCA and SMS. The *QueryType* parameter (Figure 2) is an enumeration value that indicates what type of query the client is sending. The query processing component in SMS primarily uses graph algorithms to derive a query result. In general, a query result consists of either a (network-based space) layout, an (element) network, or an (element) set. The difference between a network and layout is that a network does not include space volumes. The difference between a set and a network is that a set does not include spatial relations. In case of an LCA query, a luminaire result set is returned.

An LCA query is processed by SMS as follows:

1. The user location, which corresponds to a desk, is the start node to search the layout element network of the *Luminaire/Desk* layout (Figure 3a, user location is marked with the letter *u*) using a nearest neighbor graph algorithm. Edge

lengths are used as weights in the search. Multiple nearest neighbor nodes with the same path weight are feasible. Two nearest neighbor searches are executed: one to retrieve the *Nearest Desk Luminaire* set, and another to retrieve the *Nearest Ceiling Luminaire* set. For the user location in Figure 3a, there is one nearest desk and one nearest ceiling luminaire (marked with the letter *n*).

2. A luminaire in the *Nearest Ceiling Luminaire* set is selected as the start node to search the layout element network of the *Ceiling Luminaire* layout (Figure 3b) using a connected component graph algorithm. Barriers are defined on certain layout element relations to limit search to the whole space that contains the start node. The search returns a *Ceiling Luminaire* network (Figure 3c) which includes ceiling luminaires, surrounding subspaces (excluding volumes), and respective surrounds and adjacency elements. Initially, all node and edge weights in the network have a value of 1 – node weights in Figure 3c are already adjusted, which is done next.
3. The distance between each ceiling luminaire in the *Ceiling Luminaire* network and the ceiling luminaire that is in the *Nearest Ceiling Luminaire* set is determined with a nearest neighbor graph algorithm. For simplicity's sake, the number of edges in shortest paths are used as distance measure in the example. [Alternatively, edge lengths will be used as distance measure in system tests.] The distance is assigned to luminaire weights. Figure 3c shows an example of ceiling luminaire weights in the *Ceiling Luminaire* network. The weight of the single ceiling luminaire that is in the *Nearest Ceiling Luminaire* set is 0.
4. All ceiling luminaires in the *Ceiling Luminaire* network are selected. The resulting *Ceiling Luminaire* set includes all ceiling luminaires with weights that approximate distances to the user location.
5. *Nearest Desk Luminaire* and *Ceiling Luminaire* sets are merged into the *Result* set and returned to the client.

IMPLEMENTATION

Space Model Server (SMS)

Efficient query processing is critical for SMS to handle high query loads. Since query processing involves network traversal using graph algorithms, Boost Graph Library (BGL) is chosen to represent and query the space model (Boost 2011). BGL is a compact, efficient, and flexible graph framework that lets clients use graph representation methods and algorithms that are suitable for the task at hand. Each network element is represented by a node in a BGL graph. Each node is decorated with a set of property maps dependent on the network element's type. Edges that represent spatial relations between network elements are decorated in a similar manner. For example, there is a property map to model weight attributes of network element relations.

Communication between LCA and SMS is implemented using the Boost.Asio library (Kohlhoff 2008). Boost.Asio is a C++ library for asynchronous networking and low level input/output programming. Asynchronous network programming makes working with a large number of network connections possible.

Personal Lighting Manager (PLM) and Lighting Control Agent (LCA)

PLM is implemented as an Android application and written in Java. The full NFC support API of the Android OS version Gingerbread 2.3.3 is used in the implementation (Google 2011). Communication with IS is also implemented via the Android API.

Communication between PLM and LCA modules uses Google protocol buffers (Google 2008). Protocol buffers is a multi-platform data encoding library which enables systems running on different hardware platforms and operating systems to exchange data. For example, a client application on an Android smartphone may read and decode information sent from a server application running on Windows operating system with minimal developer overhead.

Luminaire dimming requests are sent from LCA to LAS via a KNXnet/IP to DALI gateway (KNX/ISO/IEC 2007, IEC 2003, DALI-AG 2001). A KNX/EIB driver is part of LCA to enable its communication with the gateway. LCA is implemented independent of a specific LAS such that it can be easily adapted to different types of LAS.

DEPLOYMENT

Client side modules PLM, IS, and NFC are deployed on a Nexus smartphone that runs the Android operating system. The smartphone has a built-in illuminance sensor and NFC capability. The NFC module on the smartphone detects tags within a range of ca. 1 - 4 cm.

Server side modules LCA and SMS are deployed on a semi-modern Windows OS (Windows 2000 or newer). A suitable server computer should have at least 1 GB of RAM, and at least a 1 Ghz single-core processor.

TESTING AND VALIDATION

Test room

An office room at the Department of Digital Architecture and Planning with four workplaces will be used to test and validate the system prototype. Workplace and luminaire arrangements in the test room are shown in Figure 3a. Existing luminaires are retrofitted with dimmable, Digital Adressable Lighting Interface (DALI) ballasts for, respectively, fluorescent (ceiling luminaires) and halogen (desk luminaires) lamps (IEC 2003, DALI-AG 2001). An NFC tag is mounted on each work desk at a location that is easily accessible by users.

System and user testing

The system prototype will be evaluated against functional and non-functional requirements. Scalability tests will be performed in the test room as well as in virtual environments. In the latter case, a large building will be modeled with a large number of concurrent users to determine if the system is able to maintain sufficient response times for user actions. Moreover, test users who perform the task described in the scenario will provide preliminary feedback on user satisfaction with the system prototype.

CONCLUSION AND FUTURE WORK

The proposed personalized lighting control system may be extended in several ways. Addressing the problem of shared lighting objects is of high priority for successful system deployment in real-world, multi-user environments. Conflict resolution mechanisms are necessary to determine suitable control actions for shared lighting objects in case of contradictory user preferences. Moreover, strategies for integrated artificial lighting, natural lighting and shading control need to be developed.

Applications in the HVAC, CSCW, or indoor navigation domains may be enabled or enhanced by a space model in a similar way as lighting applications. However, the space model query interface is inadequate to support query needs of domains with different space model requirements (Rosenman and Gero 1996). Query composition methods, that is, the definition of query expressions that consist of simple query sequences or query trees, could be useful to make space model queries more flexible and generic.

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