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Advanced street lighting control

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ABSTRACT

Design and control of outdoor lighting systems is a complex task, which is made even more difficult by introducing features like dynamic, sensor-based operation, multiple lighting levels and sophisticated, adjustable luminaires. This paper proposes an integrated approach, based on formal graph-based models and methods, to handle both of these tasks. The introduced formalisms help handle the state-space explosion related to the aforementioned characteristics. Control is performed by means of AI techniques (including rule-based systems and pattern matching), which is applied to the system using graph transformations. An illustrative, simple example is carried out throughout the paper, but the presented methods are highly scalable, which made them applicable to several practical projects of varying scale and characteristics.

1. Introduction

Outdoor lighting systems are usually designed and operated with several objectives in mind. These include conformance to lighting standards (i.e. provision of minimum required illuminance in given regions), minimization of power consumption as well as improvement of user comfort (which is partly due to standard conformance) and aesthetics.

Recent advancements in lighting systems bring features which may be helpful in achieving these objectives, such as multiple luminaire states (e.g. featuring more than two light levels), complex or reconfigurable geometries, different operating modes (i.e. night or emergency modes) and, last but not least, sensor-based dynamic control. Although helpful, these features dramatically increase the number of possible states of the lighting system, making its design a very complex task, which cannot be controlled by hand.

To solve this problem, formal methods such as distributed graph transformations must be employed in the design phase. These should be complemented by appropriate solutions for control, including advanced AI algorithms (such as pattern matching or automated planning) and agent-based systems.

This paper proposes a formal basis for integrated and coherent design and control of outdoor lighting systems as well as a simple example to illustrate its concepts. It is organized as follows. Section 2 describes the relationship between design and control and outlines the advantages of this approach. Section 3 provides an insight into the formal, graph-based approach to lighting design. In Section 4, a supplemented graph structure – the control availability graph (CAG) – is introduced. Section 5 adds an AI approach to lighting control, and Section 6 provides details how the rules can be applied to the CAG by means of graph transformations.

2. Design and control

Design and control of lighting systems are tasks which are often handled separately. This is usually due to the fact that tools and formalisms applicable to one of these problems are usually not universal enough to handle the other.

The proposed graph-based approach is different in that it provides a formal framework able to encompass information relevant to both the design phase and the exploitation phase, i.e.:

- spatial characteristics of the area under consideration,
- requirements regarding the illumination of individual subregions,
- parameters of the luminaires,
- all inputs and outputs, including sensors and luminary control,
- methods for selecting appropriate configurations and determining state transitions.

This approach has numerous advantages, first of which is the ability to create designs better suited to real-life exploitation based on the assumed usage scenarios. This allows systems to be controlled more efficiently, and lamp parameters may be selected more appropriately with regard to the required lighting levels. Moreover, analysis of control scenarios may positively influence sensor deployment by helping to identify missing or excess sensors

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in the system. Finally, an integrated lighting design/control process may yield more accurate logical decomposition of the area under consideration (for instance, with regard to predicted dynamics in various subregions) and trigger redesign when necessary.

Related research regarding intelligent outdoor lighting control indicates a common theme: the possibility to save energy. This has been confirmed by experiments. Outdoor lighting optimization regarding a highway tunnel, presented by Fan, Yang, and Wang (2011), has shown significant reduction of energy use. The tunnel is equipped with vehicle and luminance detectors. While minimizing energy use, the system still had to fulfill luminance requirements in order to comply with safety regulations. Guo, Eloholma, and Halonen (2008) confirm that street lighting for highways and intersections which takes both traffic and weather conditions into consideration can lead up to 40.9% energy savings.

The aforementioned solutions are tailored and tuned to particular cases. The approach presented in this paper is design-driven: design gives basis for intelligent control using AI techniques. This way, general rules, which are easily transferable to other cases, can be used for control purposes.

A proposal of a control system for complex, intelligent street lighting can be found in Wojnicki and Kotulski (2012).

3. Formalizing design

The main objective of lighting design is development of a lighting infrastructure which satisfies given criteria, e.g. a suitable illuminance level, low power consumption or other, business-oriented goals (compare with Boyce, Hunter, & Vasconez (2001)). An approach frequently applied to outdoor lighting design addresses two of these criteria, i.e. it provides optimization targeted at minimizing the input power level, while still fulfilling the mandatory lighting standards (see: Illuminating Engineering Society of North America (IESNA), 2000; British Standards Institution (BSI), 2003; Commission Internationale de l'Eclairage, 2010). Such an approach is assumed for the considered case study.

The first step towards creating a lighting design is identifying all usage/lighting scenarios for a given area. They may be related to factors like the presence and behavior of (volatile) objects, e.g. cars or persons, but also to weather conditions, current time and date, the ambient light level, etc. Potentially, each of these scenarios requires different adjustments of particular luminaires (the lumen flux values) and, possibly, different control schemes when transiting from/to other scenarios. In further considerations, we will use the notion of a *profile* which refers to a set of *requirements* regarding the illuminance of a segment. In most cases, a profile is ascribed to some subarea containing luminaires, sensors and relevant infrastructure. Thus, fixture adjustments, switched dynamically (triggered by environment state changes) and in conformance with given profiles, define a *control scheme*.

The next phase in the design process is creation of a representation of the considered area (see Fig. 1(left)) by means of a proper formal model. A formal model allows for efficient computations (especially for large-scale problems), thanks to the possible application of computational techniques which are supported by such an abstract layer (Kotulski & Sedziwy, 2012). For lighting design problems, a graph-based formalism will be used.

The considered environment representing a gas station[1] is given in Fig. 1. All elements of the environment are regarded either as solids (gas pumps, pillars, canopy, kiosk, ground area) or as dimensionless points (fixtures, sensors). A composite solid being a compound of multiple adjacent polyhedrons is represented by a hypergraph (see Sędziwy & Kozień-Woźniak, 2012), and dimensionless points are added as its supplementary vertices.

The crucial feature of the hypergraph model is that it provides a calculation grid (2D/3D) necessary to perform photometric computations. Let us note that the results of those computations may be encapsulated within attributes of nodes and edges/hyperedges. Thus, they are accessible at the abstract layer.

Fig. 2(a) shows an extremely simplified scene containing the gas pump, a section of the ground area and the canopy with its supporting pillars. All these objects are assumed to have cuboidal forms. Additionally, two fixtures and a single sensor are present. The graph model of this scene is shown in Fig. 2(b). For better clarity, we *collapse* hypergraphs representing particular solids and mark them as hexagonal vertices.

To achieve a lighting design goal (required light level with minimal energy usage), one has to solve an optimization problem, formulated at the beginning of the section, using the calculation grids provided by the graph model. It should be emphasized that the results of this phase include not only the adjustments of *internal* fixture parameters (photometric profile, inclination, dimming and so on) but also the distribution of fixtures and, possibly, sensors. For this reason, the design phase strongly impacts the control phase. In particular, a graph structure obtained in the design process creates a framework for the control task.

4. Control availability graph

The environment regarding a particular area, equipped with sensors and lamps illuminating its segments, is shown in Fig. 1. It is formally represented as a graph (see Fig. 3), called the control availability graph.

The following naming convention is assumed. A *vertex* is attributed with its type, index and any number of optional key-value pairs. Regarding the examples, for simplicity, the mandatory attributes (type, index) are expressed by labeling the vertex with the type name, the index being its subscript. Additional attribution regarding information relevant to dynamically-changing control, such as the current sensor values or indication that a particular lamp configuration is enabled, is also provided. It is presented as a third value in square brackets at selected vertices. Formally, it is an attribute value named according to a particular vertex type (see Table 1). These are used in subsequent sections.

A lamp is shown as a vertex labeled L. The configuration of a lamp is represented as C, while a segment, which is an area illuminated by a number of lamps – as S. A single lamp configuration contains parameters for a group of lamps, which achieve the desired light profile on a given segment. The parameters are expressed as labeled edges between C and L, while profiles are edges between S and C. There are the following sensors: P – presence sensor, K – darkness sensor, D – 'done fueling' sensor (indicating that the gas needs to be paid for), H – day or night hours sensor (which determines the operating mode of the station, described further in this section). There are relationships between sensors and segments, defined as appropriate edges.

Numerical indices indicate particular lamps (L_1, L_2, etc.), configurations (C_1, C_2, etc.), segments (S_1, S_2, etc.), or sensors (P_1, P_2, D_1, D_2, R_1, etc.). Formally, vertex labeling corresponds to attributes. Each vertex has its *type* and *index* attributes which hold the values (e.g.: C_2 corresponds to *type* = C, *index* = 2).

5. Rule-based approach

Analysis of the requirements indicated the following terms and rules. There are three levels of illumination: *high*, *low* and *off*. There are two modes of operation: *day hours* and *night hours*. During the

[1] http://en.wikipedia.org/wiki/File:Esso_gas_station_finland.png GNU Free Documentation License.