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Towards AI-based Distributed Lighting Control Systems

1. Introduction and Motivation

Contemporary lighting systems become more and more complex. The complexity is a direct result of available capabilities of emerging new technologies such as LED. Each of the light points can be very precisely controlled having multiple power states which correspond both to power consumption and light intensity. These provide more fine-grained control over lighting conditions. Having magnitude of states and multiple spatially distributed light points poses a challenge to control systems.

To obtain particular lighting conditions some number of light points should be activated at precise light intensity levels Which is the main task of a control system. The activation pattern (which indicates light points, their power levels) is subject to optimization according to given criteria. These can be: power consumption, light point utilization, aesthetic etc. Switching from one lighting condition to another presents yet another challenge: how the light points should be switched not causing unpleasant effects (blinking, strobe, etc.).

Furthermore the successful control should be based on a data from sensors. It allows the control system to verify if the lighting conditions are met. It would also allow to asses if there is a need to provide other conditions (i.e. illuminating or dimming certain areas). Depending on particular application there should be different sensors considered such as: time, light, presence, movement etc.

This paper focuses on the control issue. The light points topology and their capabilities as well as the lighting conditions and sensor output need to be defined in a formal way. To provide a successful control a pattern matching between the sensor output and the lighting conditions is to be provided. Upon successful match a sequence of control commands is generated. The commands are directed to proper light points based on their topology. Generating such sequences requires planning and optimization. Alternative control sequences, regarding particular optimization criteria, could also be considered.

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To provide pattern matching and to cope with the complexity, applying certain Artificial Intelligence methods is proposed. In particular, using rules and implementing a Rule-based System capable of inferring appropriate control is further discussed.

2. Related Work

Artificial Intelligence methods have been used previously in control-related systems. Gensym G2, Tiger and SCADE should be mentioned here. G2 is a general expert system which can be applied to variety of problems ranging from Business Rules to Real-Time Control [7]. Among other applications it has been successfully applied to control Unmanned Aerial Vehicles (UAV) or Power Systems management. Tiger (created by Intelligent Applications Ltd, presently Turbine Services Ltd) is a real-time rule-based system designed to diagnose gas turbines [9]. It is estimated that the system alone has brought huge savings thanks to early detection of possible failures. The project initially was researched at LAAS in France [3]. There are also languages and run-time environments dedicated to handling rules, such as CLIPS, Jess or Prolog. SCADE (Esterel Technologies) should also be mentioned here which is a complex declarative programming environment. It is actively used by Airbus and Eurocopter.

Most of the intelligent lighting research focuses on smart buildings. It includes both office and home spaces. Well defined zones (predefined areas) with sensors deployed are used to obtain information about the environments state. Taking into consideration user lighting preferences, inhabitant tracking, daylight intensity detection and window blinding control leads to energy savings [5]. The above solution is based on agents and uses hidden Markov model for inhabitant tracking.

Similar approach is proposed in [6]. It also focuses on in-building operations. Additionally the control system either sends control commands to actuators or informs the inhabitants that there is a need to switch certain light points, blinds etc. to reduce power usage – performing educational role. Detecting outdoor lighting conditions is based on a complex sky model.

[4, 1] present an experiment conducted in an office space which goal is to reduce energy consumption. Having given lighting requirements (desired luminosity at certain locations) and multiple light points by turning or dimming some lamps off the goal is addressed. To conduct the optimization process Simulated Annealing is used.

An outdoor lighting optimization is presented in [2]. A highway tunnel lighting case is discussed. The tunnel is equipped with vehicle and luminance detectors. There are also some luminance requirements given to comply with safety regulations. Applying the proposed control based on data from sensors leads to energy savings.

All presented approaches indicate a common theme: possible energy savings due to intelligent control which is often confirmed by the experiments.

The main goals of the proposed approach are: energy savings, increased safety, and last but not least aesthetics. Comparing with the approaches presented above it is characterized by the following features.

- It is topology driven, tailored to handling complex topologies, complex lighting setups, formally defined with hypergraphs.
- It is well scalable employing agent-based approach.
- Outdoor applications (squares, streets, parks) are targeted.
- It introduces lighting profiles employing modes of operation. The system switches to proper lighting profile upon information from sensors.
- Handling different control scenarios such as: normal or emergency conditions, security threat situations, etc. is provided by introducing a hierarchy of profiles.
- The profile hierarchy is formally defined with hypergraphs with well defined transitions among them.
- Smooth, aesthetic transitions upon profile switching is provided.

It needs to be pointed out that using graph and hypergraph representations in the presented approach makes it applicable to any level of problem's structural complexity. Their expressive power is sufficient to describe complete topology [8]. The added value of this method, compared with others, is its scalability supported by mentioned formal model and parallel computation methods based on agents, described in the following sections.

3. Problem Description

A General Environment Model (GEM) is proposed. It consists of architectural space, light points and sensor devices. The architectural space represents an urban environment consisting of buildings, roads, sidewalks, green spaces and so on. A light point corresponds basically to the street luminary. It is characterized by a predefined set of properties, e.g. luminary coordinates, pole height, fixture type (incl. power, light distribution), lamp fixture overhang etc. Similarly the sensors have their properties and spatial distribution defined.

We assign a set profiles of illumination to a particular component of an architectural space. Such a profile is defined by both the existing lighting standards, obligatory for a given area class and by an environment state expressed in terms of weather conditions, traffic intensity and other parameters supplied by sensors. Due to the above a lighting profile vary (or precisely, a system transits between different profiles) in time dependently on an actual external conditions. The detailed presentation of a profile concept is contained in Section 3.1.

Our general goal is to control each individual luminary (i) in the compliance with actual lighting profiles, (ii) with the minimum power supply, (iii) avoiding rapid lighting level switching (luminance level has to be smoothed over time).

An example environment describing a park is given in Figure 1 (mind that varying topologies and functions can be considered this way: streets, squares, public areas etc.). Light points are indicated with circles labeled with 'L'. Presence sensors are circles labeled with 'S'. There are also two triggering objects indicated with human silhouettes. In general these can be any objects (cars, trolleys, bicycles etc.), assuming that they are properly classified by the sensor grid. Hatched areas represent sensor range, defining Sensor Areas. Lamp Areas are also part of the GEM, indicating which particular lamp is capable of illuminating which areas, however they are not showed in the Figure for clearer presentation.

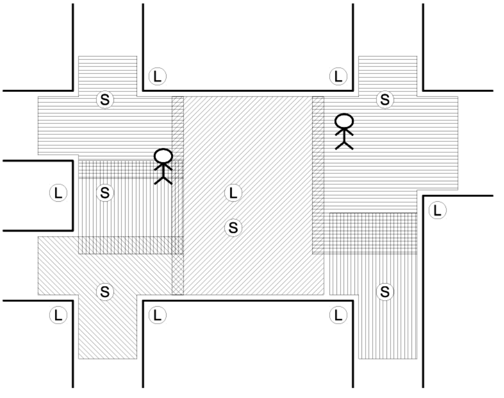

Fig. 1. General Environment Model: L – light points, S – presence sensors

The description of the environment is provided as a graph structure. Some additional information regarding parameters and dependencies among provided entities (sensors, lamps, objects) can also be given. Availability of such information depends on particular needs of software components of the proposed system and control requirements regarding particular case. They are discussed in the following sections.

3.1. Profiles

A lighting grid forms a complex system of light points. The points are spatially distributed, possibly non uniformly. Each point has certain parameters, in addition to its location, such as available output power levels, energy consumption, direction etc. Each point can be managed, controlled separately to make optimization of the entire grid according to chosen criteria possible.

Lighting control is subject to profiles. A profile defines a mode of operation for a lighting grid for particular purpose. It provides behavioral model under certain circumstances, precisely defining lighting conditions. Choosing a profile can depend on such factors as natural lighting, weather (snow, rain, fog), time (time of day, working days), social events, energy shortage, traffic etc.

Since some profiles might depend or subsume each other, they can form a hierarchy. In general, this hierarchy can be expressed as a hypergraph. An example set of profiles for public access areas are presented in Figure 2. There are two major profiles Normal and Emergency defining lighting conditions for regular and emergency operations. Within regular operations there are Tracking and Standby profiles defined. The Standby describes a profile which provides minimum lighting, while Tracking illuminates regions in which some activity can be detected i.e. people presence.

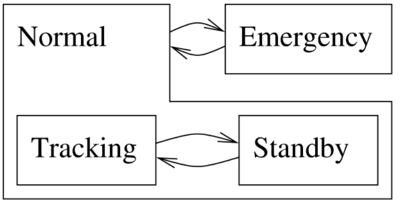

Fig. 2. Lighting Profiles

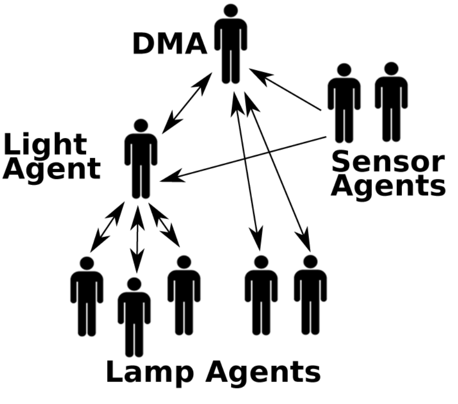

Fig. 3. Architecture of a multiagent system

4. Agents

The assumptions concerning the environment model and system goals imply the high complexity of related computations and therefore the "naive" models assuming a simple geometric representation of a whole urban space are ineffective. In their place one has to introduce a fiexible model, expressive enough to cover all system components and applicable as a distributed computing. Such properties have graph representations. It formalizes a behavior of a software controlling the lighting system. A piece of such a distributed software will be referred to as an agent.

Using a multiagent approach to execute control tasks improves performance of a city lighting system. The problem is an explicit synchronization in the case of concurrently working agents. Avoiding time-dependent errors for an explicit synchronization requires a signif-icant effort and is a complex issue. For this reason we propose an implicit synchronization method based on separation of data modifiable by agents.

In a multiagent system we distinguish the following types of agents assigned either to physical components (lamps, sensors) or to abstract entities as software modules (Fig. 3).

- **Decision-Making Agent** (DMA) – main control agent. It is responsible for collecting sensory/diagnostic data, lighting control in the *empty mode* (i.e. when no objects are present in a scene), creating *light agents* when objects appears in a controlled area.
- **Sensor Agent** – collects data captured by a sensor device and relays them to *light agents* or a DMA.
- **Lamp Agent** – located over the lamp driver layer. This agent keeps direct control, via a lamp driver, over a lamp behavior (dimming, switching on/off) and intermediates between a light agent a driver. It transmits all exploitation/diagnostic data concerning a state of the device.

  Lamp agent receives control messages periodically and goes to an emergency mode (lamp in certain state i.e.: switched on) if communication is broken.
- **Light Agent** (LA) – manages a set of individual luminaries via lamp agent. If some object(s) appears in a scene then DMA receives information from sensor(s) and determines a set of lamps involved in illuminating a corresponding area. Next a light agent is created by a DMA and ascribed to that set. The control tasks are delegated to this light agent together with the relevant subgraph representing the area and entities (in particular luminaries) being controlled.

5. Control

The following section describes the Decision-Making Agent (DMA) and the Light Agent (LA) architecture, behavior, and necessary data which is given in Figure 4.

The main difference between DMA and LA is that DMA covers profile switching for certain area, given by GEM, if there is no data coming from the sensors – it can be called a static control. Upon sensor activation DMA spawns LAs to carry out dynamic control based on sensor data. In general, for control purposes current lighting profile, sensory data, and the lamp states – the state of the entire system – are taken into consideration. As a result information regarding switching a profile for a given area is synthesized.

There are two issues to address. Pattern matching applied to the current system state upon which appropriate control sequences are triggered and smooth transitions between lighting profiles. The first issue is addressed by the AI Control, the second one by the AI Smoother. The main focus regards the AI Control here.

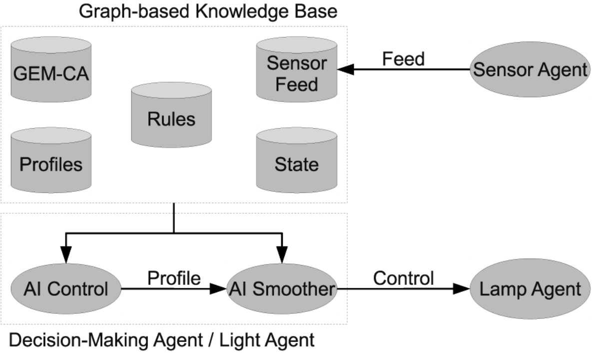

Fig. 4. AI Control System Architecture

The General Environment Model (GEM, described in Sect. 3) needs to be extended with additional information regarding Control Availability (CA). CA indicates indirectly which sensor feeds can be used to control particular light points. Since each sensor covers certain area (Sensor Area), upon sensor activation this particular area should be illuminated accordingly to deliver proper lighting profile. The illumination is provided by the light points which are capable of covering the Sensor Area.

An example CA for the proposed GEM (Fig. 1) is showed in Figure 5. Edges between lamps and sensors are introduced. An edge between a sensor and a lamp indicates that area covered by the sensor can be illuminated by the given lamp. The proposed formalism is similar to the Control system infiuence graph introduced in [6].

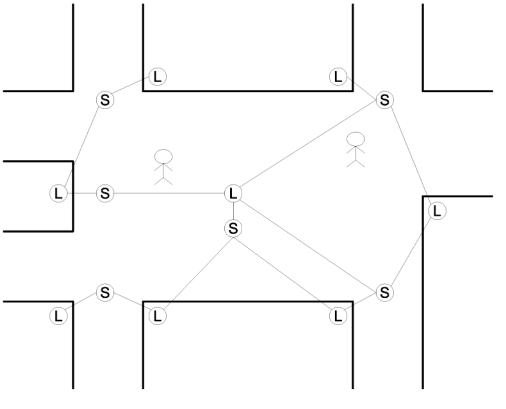

Fig. 5. Environment Model, Control Availability Graph

CA allows to partition entire environment into manageable subsections depending on the incoming data feed. The partitioning is carried out if there is incoming feed from the sensors and it is parametrized by them. It allows to focus the control process on particular substructures in GEM instead of considering entire system. Furthermore, it enables DMA to spawn multiple LAs (Light Agents) if there are multiple partitions identified. Some examples are given in the subsequent sections.

Having a CA enhanced GEM (GEM-CA) the AI control can match current conditions and a pattern of active sensors (optionally) and decide to switch to a different profile for a given area. The matching is executed by a rule-based engine.

Each rule consists of conditions and decisions. A rule conditions are: current system state, profile, and GEM-CA sub-patterns (optionally for LA, see Sect. 6 for details). Rule decisions regard the profile which should be switched to.

Upon switching a profile an unpleasant, in terms of aesthetics, effect can take place (i.e. an abrupt lighting condition change, blinking etc.). To compensate for that the AI Smoothing module is introduced. It generates a sequence of control commands which gradually switch between lighting profiles, providing a smooth transitions, in terms of luminosity change.

6. Case Studies

Given GEM discussed earlier let us consider a situation in which a single person is detected (Fig. 6a). There is a person P1 which triggers a sensor (S). According the GEM-CA three light points can be controlled then (dotted lines between S and L). The rule-based system (AI Control), having current system state, profile and pattern matched makes a decision to switch to other profile.

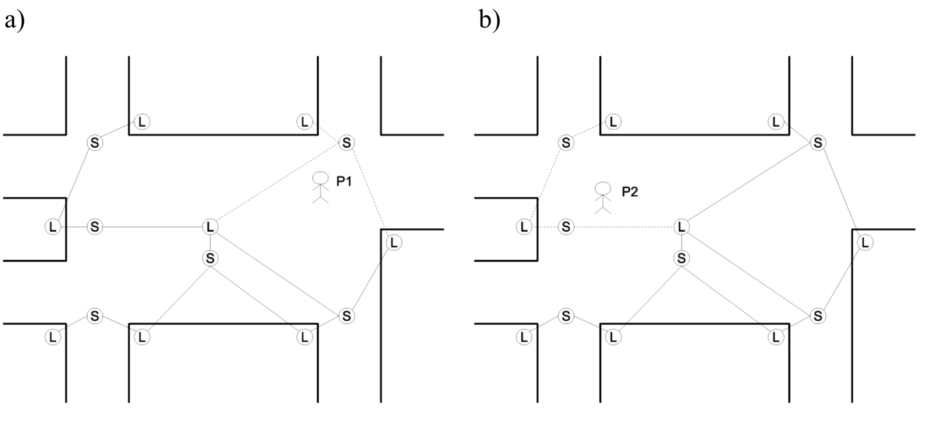

Fig. 6. Environment Model: an object detected

Similar situation takes place in Figure 6b. However this time person P2 triggers two sensors. The pattern is different in terms of sensors triggered and control availability. Depending on particular topological properties of lamps and sensors these two cases can be handled by the same (equivalency between two presented with dotted lines sub-graphs in Figure 6a and Figure 6b) or different rules (if there is no equivalency).

A different situation is depicted in Figure 7a. There are two persons P1 and P2, thus two separate sub-graphs (such a case can be handled by separate instances of LA employing distributed agent-based nature of the proposed approach). Comparing with previous examples the difference regards number of sub-graphs identified, thus number of agents.

In Figure 7b the case changes. There is only one sub-graph even if there are two persons P1 and P2 triggering three sensors in total. Comparing it with Figure 7a the same number of lamps is to be activated. The central lamp (in the middle of the Figure) provides auxiliary light supporting profiles for the triggered sensor areas only. It does not provide light to cover profile change in the central area. Thus, overall energy consumption is lower comparing with a situation if the central sensor is triggered (assuming that triggering sensors changes current profile to a brighter one). The rule-based system matching such a situation can optimize energy consumption by deciding to increase light emission of the central lamp simultaneously dimming the outer ones – retaining the same luminosity levels at lower energy consumption rates.

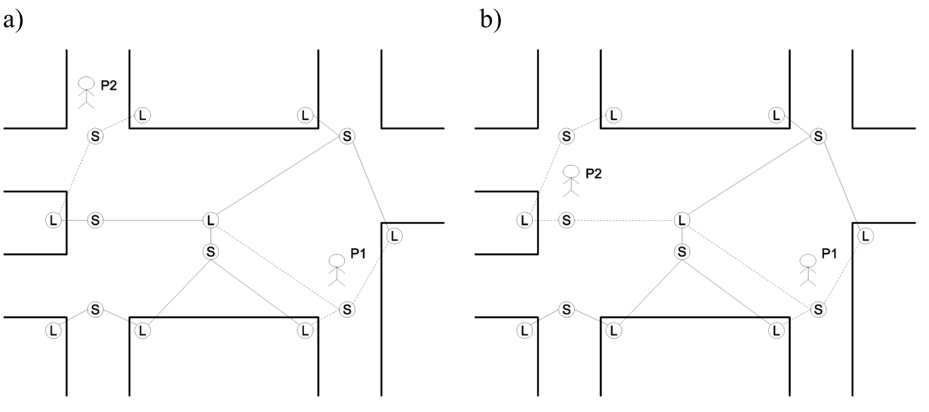

Fig. 7. Environment Model: two separate objects detected

7. Summary

The paper discusses an approach which is targeted at obtaining maximal benefits of advanced lighting technologies, like light emitting diodes (LED). The benefits are expressed in terms of improved energy efficiency (i.e. lower power consumption) or citizens quality of life. Applying proposed solution one could use intelligent control methods which functionality goes far beyond simple preset lighting scenarios as it is present in existing commercial systems.

The main problem to overcome is a high complexity of control algorithms related to a size of a state space compound of lighting profiles, fixtures' working parameters and varying environment conditions. The proposed method, designed for solving this issue, uses decomposable graph representations of the environment under control, and multiagent system deployed on it. An important component of the system is a rule-based engine, adapting lighting control parameters to actual environment needs.

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