Smart Lighting in Multipurpose Outdoor Environments: Energy Efficient Solution using Network of Cooperating Objects.

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Abstract. The first applications for smart environments targeted well-scoped spaces and appliances. These applications were strong drivers to advance Wireless Sensor Networks (WSN) and the Internet of Things (IoT). With the evolution of the technological base, more complex environments became the new targets. The concept of cooperating objects (CO) enables further advancement of IoT and helps to grasp the multiple aspects of these environments. This paper describes smart lighting application for the multipurpose outdoor environment at the university campus area implemented following the new paradigm. The application is aiming efficient use of energy and future integration with associated industrial systems.

Keywords: cooperating objects, embedded devices, web services, energy efficiency, smart lighting.

1 Introduction

Early smart applications targeted stand-alone appliances within small living and/or work spaces. With the adoption of more mature technology, it became possible to embed smart applications in more complex environments, exhibiting different levels of demands and requirements depending on the target domain (e.g. cities [1], factories [2], and lower level industrial environments [3]).

Smart applications target enhanced user experience while facilitating efficient use of resources. There are common challenges across all the application domains that complicate the achievement of the objectives. These challenges include, but are not limited to: multitude of purposes for which the same environment may be used, big amounts of users with different profiles, and dynamics of ambience.

WSN and IoT were successfully applied to implement the early applications for smart environments [4, 5], and continued to evolve driven by newly appeared challenges. The concept of CO [6] bears on the same technological base, as IoT and WSN and is perceived as foundation for the future IoT [7]. This approach enables creation of sustainable smart solutions for complex applications in such domains as Smart Grid [8].

This paper describes an approach to implementation of smart applications in a multipurpose environment following the cooperating objects paradigm. The use case presented is a smart lighting application for outdoor docking environment at a university campus aiming improved user experience and reduced energy consumption. In addition to primary objectives, the solution is intended for the integration with industrial systems located inside the building. The paper is structured as follows: Section 2 provides the research background discussing the technological considerations for smart lighting applications; Section 3 describes the implemented smart lighting solution; Section 4 draws the conclusions and outlines the future work.

2 Technological Considerations for Smart Lighting Applications

2.1 Illumination

Lighting conditions have strong impact on everyday life and individual work performance [9, 10]. Illumination accounts for 5 to 10% of total energy consumption on the planet [11], with lighting systems presenting huge potential for energy savings [12]. It is therefore of crucial importance that smart lighting applications should aim efficient resource usage. Most of the savings can be achieved via suitable (multiple type) control strategies [13], that have proven so far more effective than simple personal, institution, occupancy and day lighting driven control [12].

Recommended illumination levels (as produced by the Illumination Engineering Society) vary from 100 lux in the warehouse areas to 5000 lux for fine inspection operations [14]. In multipurpose environments, compliance with levels tailored for the specific needs of one working environment at hand is achievable via a control strategy allowing to switch between pre-set lighting modes correlated to specific user needs.

As far as energy consumption of lighting solution is concerned there are a number of aspects to be taken into account. The luminous intensity drops rapidly as distance from the light source to the observer increases. Because of the non-linear nature of this dependency, implications of different lighting modes on energy consumption are not as straightforward as it may be initially expected [14]. Although there are simulation tools available allowing to estimate the energy consumption of lighting applications, it has been found that simulations tend to overestimate savings [12]. Therefore, real measurements are needed in order to evaluate the energy efficiency of a lighting solution in place.

The identified challenges may be addressed by considering LEDs over conventional light sources and by implementing smart lighting control customized for the specifics of the environment. Numerous lighting solutions targeting energy efficient performance were developed in previous decade, actively exploiting low consuming light sources, control techniques targeting low energy consumption [15] and the combination of both [16]. The challenges of adopting the best practices of smart lighting solutions are related to the fact, that each application of this kind must be tailored to the needs of the dedicated users and consider peculiarities of the specific environment. On the other hand most of the recent solutions rest on same core architectural paradigms, discussed in the following section.

2.2 Architectural paradigms

WSN technology is used for many different applications, including structural health care monitoring, habitat monitoring, fire detection or ambient intelligence [2]. A WSN or WASN (wireless sensor and actuator network) is composed of a set of nodes distributed over an area of interest. The nodes are able to sense, process, drive, store and communicate. The network produces large amounts of raw data which then sent to the central server via sink nodes. Some variations of the concept were proposed by the research community looking to enhance either the autonomy of the network (Autonomic Sensor Networks [17]) or data processing and reuse through dynamic tagging of semantic information (Semantic Sensor Networks [18]).

Leveraging RFID and WSN, the IoT aims to break the border between physical and virtual reality through the creation of objects with a virtual representation, which can be integrated into a network of a global scale to interact with each other.

A generic definition is formulated in [19] as follows: *"The main tenet of the IoT is extension of Internet into physical world, to involve interaction with a physical entity in the ambient environment".* The entity may be an entity, a device (the means of integration of the entity with the virtual world), a resource (the software component), or service (defines standardized interfaces and processes for interaction with entities).

There are many definitions of the IoT proposed [20], with a definition focus shifting in time from the objects themselves to their communication capabilities. The notion of *"cooperative IoT"* can also be found in the literature [8]. Despite the focus shift, there are three core features mentioned across all definitions: (1) global scale of the application, (2) big amounts of devices, (3) heterogeneity of the devices.

Succeeding the IoT, the notion of cooperating objects emerged initially defined at the abstract level in [21] in the following way: *"... a Cooperating Object is a single entity or a collection of entities consisting of: Sensors, controllers (information processors), actuators or cooperating objects that communicate with each other and are able to achieve, more or less autonomously, a common goal".* While the components of an object are provided in the definition above, the term cooperation does require further clarification.

In [6] cooperation is defined as *"the ability of individual entities or objects to use communication as well as dynamic and loose federation to jointly strive to reach a common goal, which will typically be a goal in sensing or control".* A similar explanation of cooperation is given in [8].

Dynamic cooperation relying on complex messaging patterns with nested messaging threads is highlighted as the minimum technology needs to make object integration combining both visions a reality [22, 23].

The heterogeneity of devices is resolved by using semantic web service (SWS) middleware for in embedded devices [24]. This enables CO to be used for complex cross-domain applications, e.g. smart grid enabling smart houses to communicate with energy providers, marketplaces, alternative energy sources, etc. [8].

WSN and the IoT are paradigms that provide tools and methods for implementations of the solutions for complex smart environments. The approaches are often used side by side complementing each other in order to fulfill all the needs of the unconventional use-cases. This becomes possible due to the similarity of the technological base, which converges into the notion of CO.

3 Case Study: Smart Lighting Application

The solution described in this paper was designed to provide appropriate illumination for the multipurpose outdoor environment in a specific utilisation mode using low amounts of electrical power.

The section is split in five parts, dedicated to the description of the testbed (Section 3.1.), analysis of the utilisation modes of the area (Section 3.2), description of the designed architecture (Section 3.3), implementation and testing (Section 3.4), and the opportunities for integration with other industrial applications (Section 3.5).

3.1 Target Environment

The proposed solution is intended for the backyard area auxiliary to one of the buildings of Tampere University of Technology (Tampere, Finland) showed in Fig. 1. The area is used for a variety of purposes, including:

- Students and personnel everyday access to the building via two entrance doors.
- Load/unload of material /equipment to/from trucks via two additional dedicated doors.
- Parking purposes (there are several parking spaces in the area).

The zone is illuminated with four lamps, which are turned on and off following the work time schedule and security guidelines (i.e. some of the lamps are on during the night time to provide minimum illumination to the area); furthermore, the lamps are always on during the darkest period of winter.

The existing operational pattern fulfils the basic need for lighting, but does not consider such important aspects as current utilisation mode of the area and nature of the environment hosted by the building. As it was previously mentioned, there are different types of actors attending the area: students, research and support personnel, and vehicles of various scales. Each of the actors has own purpose when visiting the area, thus lighting conditions tailored for particular utilisation scenario could facilitate the goal achievement and offer better user experience to the users of the area. The part of the building facing the area considerably differs from average study blocks, being more similar to industrial environment, rather than administrative building. The area is actively used as a docking station, and preparations for load and unload operations could become easier if the lighting was automatically adjusted to the activity (i.e. proper lamps were turned to the need intensity to illuminate the working area).

Fig. 1. Views of the testbed area: view to the front wall with access doors and legacy lamps mounted and a view to the parking area.

In addition to the abovementioned problems, the existing lighting installation lacks energy efficiency due to the type of lamps used, applied control strategy and lack of dimming capabilities. These obstacles are easily overcome by migration to LED lamps with ballast offering dimming functionality, which is expected to turn into even bigger savings as cold climate prevents overheating of the diodes.

3.2 Defining the representation of the area state

The key to the improved user experience lays in the knowledge on the current status of the area. Several criteria were considered during the study of the presented multipurpose environment. The most descriptive parameters, selected for the implementation are:

- *Users present*, indicating both the fact of presence and the category of users;
- *Weather conditions*, focusing on the climate dimensions influencing the visibility;
- *Illumination level* provided by the natural conditions.

Table 1. Profile dimensions.

		Weather conditions			
Illumination level	**Users present**	Clear	Mist	Rain	Snow
Above threshold	Personnel	P_{111}	P_{112}	P_{113}	P_{114}
	Truck	P_{121}	P_{122}	P_{123}	P_{124}
	Both	P_{131}	P_{132}	P_{133}	P_{134}
	None	P_{141}	P_{142}	P_{143}	P_{144}
Below threshold	…				

The notion of profile (P) was introduced in order to combine multiple criteria in one parameter, to uniquely identify the superposition of the dimensions as shown in Table 1. Each profile is marked with unique identifier $Pijk$ where indexes stand for one of the alternative values of the profile dimensions (e.g. P_{111} corresponds to a situation when there are people in the area, the sky is clear and it is bright outside).

Each profile is mapped to a specific *lighting scene (S)* - a collection of operating modes to be assigned to each lamp on-site in order to provide the desired lighting conditions. The range of operating modes varies depending on the lamp and may consist of either "*on*" and "*off*" modes, or include a set of intermediate stages if dimming features are available.

Table 2. Profile to Lighting Scene mapping.

P	**Lamp operating modes (% of total power)**				**S**
	L_1	**L_2**	**L_3**	**L_4**	
P_{111}	0	0	0	0	S_1
…	…				…
P_{244}	30	50	50	0	S_m

Table 2. illustrates mapping between profiles and lighting scenes. It is important to realize, that total amount of lighting scenes is smaller than the amount of profiles, because same combination of lamp operating modes may apply to more than one profile.Therefore the approach results in a reasonable number of lighting scenes to be set up. The provided tabular representations were used as input for the algorithm design, helping to identify possible changes in future related to changes in amounts of lamps and profile dimensions, as hard-coded implementation prevents the scalability of the solution.

3.3 Architecture

The application was designed to serve the two purposes: provide users of the area with lighting conditions adjusted to their needs, provide detailed information about the energy consumed by the installation. The first objective can be easily achieved through sensing of the environmental conditions and user detection and consequent mapping of the detected profile to the required lighting scene. The second objective puts requirement for synchronization of the measurements recordings with the profile changes and raises the question about the degree of granularity of energy measurements. Considering the need to investigate the energy consumption patterns and obtain detailed information about the performance of the updated lighting system, it has been decided to measure consumption of each individual lamp block installed.

The designed architecture is shown in Fig. 2. Smart lighting application . Due to the small scale of the target area, only four proximity sensors (denoted as PS1-PS4 in the figure) are needed for user detection. Sensors allow detecting the direction from which a user is approaching the area as well as distinguishing between trucks and people. Additionally a Temperature-Humidity-Light (THL) wireless sensor nodes are needed to sense illumination level and weather conditions. The complete information about weather conditions is formed by data from THL sensor and weather web service, which receives full weather profile of the location from a third party weather service (Weather-Yahoo![1]).

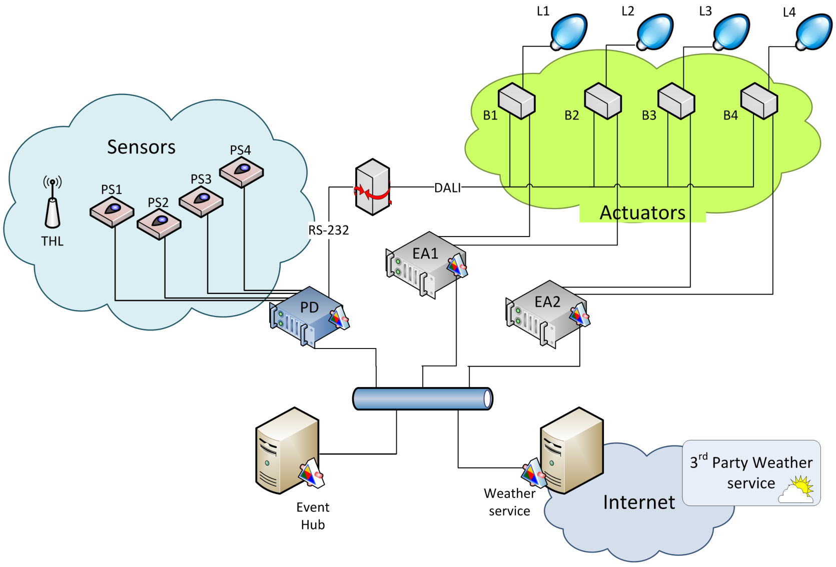

Fig. 2. Smart lighting application architecture

The command application is distributed over three embedded devices, supporting SWS. The first node (denoted as PD in the figure) hosts the main application, receives input data and communicates commands to the lamps. The other two devices (EA1 and EA2) are energy analyzers; they are intended to measure the individual energy consumption of the lamps installed. The required amount of energy analyzers depends on the amount of actuators (i.e. ballasts) and the required granularity of measurements. Each actuator in turn may serve several lamps. Its capacity is limited by the total power of the load attached.

Targeting detailed measurements of energy consumption, each of the lamps is provided with a dedicated actuator. The main controller communicates with individual luminaires via a gateway, which transforms the messages received via serial port into native Digital Lighting Addressable Interface (DALI) messages, understood by the lamps' ballasts.

Finally, all three command devices feed the events reporting measurements and status change for further archiving or use in adjacent systems.

3.4 Implementation and testing

Devices used for the pilot implementation, except the RS-232/DALI gateway, are shown in Fig. 3. Devices hosting the command logic are three S1000 RTU modules:

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[1] http://developer.yahoo.com/weather/

one with extension for wireless communication (PD) and two with E10 expansion modules for monitoring of energy consumption (EA1 and EA2). The outputs of the proximity sensors are wired to the digital inputs of the PD, and W-Z-THL sensors are communicating the measurements via ZigBee PRO protocol. Each of the energy analyzer allows to measure energy consumption and related parameters for three phases. In presented scenario, every phase is assigned to particular ballast and each analyzer is in charge of two ballasts, helping to distribute evenly the processing load. The ballasts are integrated in the luminaires and are located behind the light sources.

Fig. 3. Hardware components of the implementation: LED lamp with integrated ballast, proximity sensor for outdoor use, wireless THL sensor node, two devices S1000 with wireless communication and energy analyzer expansion modules.

The command functionality is realized through a set of distributed control and monitoring applications. Programs run in S1000 nodes are implemented in Structured Text (ST) language of IEC 61131-3 standard. The weather service is implemented in Java programming language using the Spring framework. The application uses the Weather-Yahoo! API to obtain weather information and interpret it in terms of visibility characteristics defined in Table 1. This information complements the values obtained from THL sensors and helps their adequate interpretation.

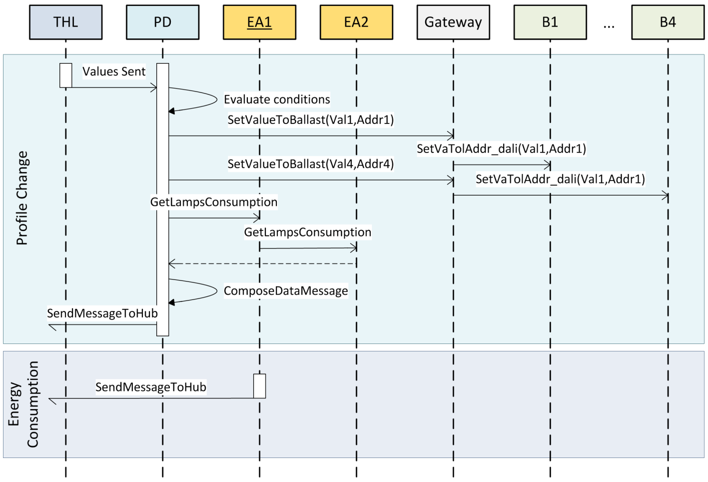

Fig. 4. Sequence diagrams of possible operation scenarios

Control and monitoring functionality is implemented in parallel and there are two processes executed in parallel in the devices. Sequence diagram in Fig. 4 illustrates messaging patterns of two possible scenarios: profile change and energy consumption measurements.

When main application receives sensor data it identifies the corresponding profile. In order to avoid big amounts of nested *"IF"* statements, the profile ID is computed as function of tree profile variables. Then the associated lighting scene is identified. If the computed scene is different from the current one, main application sends a series of messages to the ballasts via gateway in order to set up the new scene. Then a notification sent to the energy analysers about the profile change. This message triggers response messages from analysers, containing data on energy consumption. Main application receives data from the analysers and composes a message to be sent to the data acquisition application. It is important to obtain the energy performance information from all the lamps when the profile changes. Therefore, when the first analyser receives the request from the main application, it updates own knowledge about the profile and composes a message containing requested energy data. But, instead of sending the data to the requesting device, it passes the request together with own reply to the second analyser. The second device also updates its profile data and ads requested energy information to the message received from the first device. Finally the information is passed to the main application, where it is used to compose the message to be sent to the adjacent systems via the Event Hub.

Besides the scenario described above, energy analysers perform regular measurements of energy consumption and related parameters. The frequency of measurements is dependent on the current profile. In order to reduce amount of traffic and detect abnormal consumption patterns, measured data are sent to the data acquisition application in the two following cases:

- The nominal time interval defined for the given profile has elapsed;
- The amount of total energy consumed has increased for a value bigger than the threshold defined.

The abovementioned criteria are applied to each phase separately, as different lamps connected to same analyzer may be set to different operating modes in certain lighting scenes.

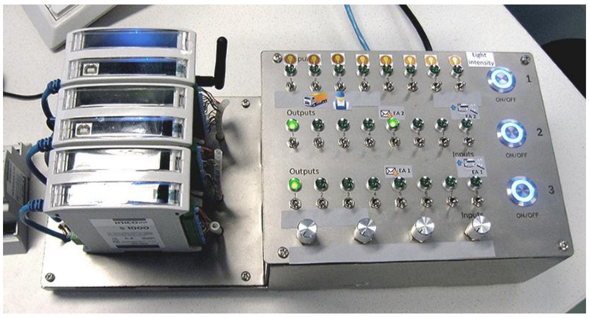

Fig. 5. Evaluation testbed.

The control box, containing the S1000 modules, is located inside the building, while the lamps and sensors are located outside, which complicates the balancing and commissioning. The correctness of the logic and message flows has been verified in the testbed as depicted in figure Fig. 5. User presence was simulated by changing the status of digital inputs of the PH device and the light intensity was illustrated through the amount of digital outputs turning on in the same device. Dedicated digital outputs of energy analysers were used to track the message flows, both between the devices and to the external applications.

3.5 Integration with Industrial Applications

Support of SWS at the device level enables direct integration of the solution with the other applications requiring the information produced by the smart lighting application. Possible integration scenarios are considered in this section.

During its execution, the designed smart lighting application produces data sent to the data acquisition application for storing. However some of this information may be used in other real-time monitoring and control applications.

As most of the data generated by the application relates to energy consumption of the ballasts and their operating modes, it can be included in energy monitoring applications as a separate set of parameters as well as a component of a composite key performance indicator (KPI) e.g. total energy consumption of the site. For the discussed case-study the site consists of the testbed depicted in Fig. 1 and the neighbouring facilities of the Factory Automation Systems and Technology laboratory hosting the production line (Fig. 6.). The line consists of 10 manufacturing cells, each containing at minimum one robot and a conveyor system. The line is capable of drawing 729 different layouts of mobile phones, using different combinations of frame, keyboard, and screen types. Cell 1 is in charge with determining whether incoming pallets are occupied with finished products and they need unload to be performed on them, or they need further circulation in the line. Quality inspection takes place also here via a machine. The buffer is implemented at Cell 7.

Fig. 6. Production line.

The integration becomes possible due to the availability of the Event Hub (see Fig. 2), receiving the WS messages from the command devices and directing them to the subscribed applications. A client application was developed to receive the messages from the smart lighting application and store it in the MySQL database (DB). It subscribes to for the required messages from the hub, parses them following the information on the system configuration contained in the dedicated XML file and stores information in the database using Hibernate library to interface the DB.

From the perspective of the aims of the lighting application, integration with shop-floor systems is required for truly holistic control strategy both in the manufacturing site and related outdoor area, as well as improved user experience. Extending the described setup to a bigger scale, data received from the proximity sensors may be used to create notifications for personnel and machines about readiness of the docking area for load and unload operations, avoiding centralised control and allowing emergent behaviour of the system. Smart lighting application, in turn, could benefit from receiving of information from the above mentioned applications or the line controllers via the event hub. This opportunity enables implementation of light control scenarios driven by the status of the production environment, e.g. setting up lighting scene required for loading and unloading operation as soon as both truck and line are ready for the process to be started, avoiding influence of human factor in the environment adjustment process which can be regulated by safety and security policies. It could also save a lot of time for the personnel, especially when needed lighting conditions are provided by a big amount of lamps with individual manual switches.

4 Conclusions and Future Work

The notion of CO relies on the technological base similar to one of IoT and WSN, and comprises features allowing taking applications for smart environments to a new level. It enables creation of sustainable smart solutions for such complex environments as smart grid, urban transportation systems, etc.

The paper presents an implementation of smart lighting application in a multipurpose environment following the CO's vision. The use case presented is a smart lighting application for outdoor docking environment at a university campus. The information about the status of the testbed is acquired via a set of wired and wireless sensors and the core functionality is implemented in three networked embedded devices featuring SWS middleware. The application evaluates status of the environment, and manipulates the lamps' ballasts in order to set up proper illumination. Additionally, it measures the energy consumption of individual ballasts allowing evaluation of control strategy from energy efficiency perspective.

Future work will concentrate on such incremental improvements of the solution as fine-tuning of the lighting scenes and optimisation of control application, optimized device and application configuration, as well as its further integration with tools for holistic energy management.

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