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WSN-based Intelligent Visual Performance Management in Tropical Buildings

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***Abstract*—This paper presents a prototypical implementation of WSN-based daylight-responsive lighting and shading systems control in buildings that utilizes real-time sensing. This system can control the position of window blinds and the states of the luminaires to achieve the desirable visual comfort and energy efficiency based on the weather conditions and occupant activities. We first present the system architecture. Subsequently, the prototypical implementation is demonstrated. The outcome of this effort is expected to further articulate the system functionality and control algorithm towards implementations in real-life built environments.**

I. Introduction

Given the enormous challenges associated with managing solar heat gain, daylighting, and glare issues, multiple serious efforts are needed to curtail thermal and lighting loads. Specifically, modern commercial buildings are frequently affected by shortcomings in the configuration and operation of building management and information system, resulting in sub-par visual comfort and poor building performance. Nonetheless, as a city-state with 100% urban population, building sustainability is of particular importance to Singapore. Second only to the industry sector, the buildings sector consumes more than 30% of Singapore's electricity production [1], in which 20% is spent on space lighting. Located in the equatorial belt, the sun is almost directly overhead throughout the year. The introduction of daylight into buildings may also increase the solar heat gain of the buildings. For the buildings in the Tropics, this may require additional cooling effort from the air-conditioning systems. Thus, compared to temperate climate, it has more potential and challenges to achieve a sustainable built environment via utilizing the daylight to replace or supplement the electrical lighting without affecting the overall energy efficiency of the building operations.

In addition to energy conservation, proper daylighting can have a huge impact on occupants' visual comfort, and thus their health and productivity [2]. It is therefore equally important to take into account of occupant activities and their perceptions towards daylighting. In a survey with office occupants [3], it is found that daylight is preferred to electrical lighting. Furthermore a post-occupancy evaluation survey in a modern high-rise commercial building also reveals that some form of automatic lighting and window shades controls are well received by occupants [4].

To address these concerns, this paper presents a research effort toward a WSN-based approach to intelligent visual performance management in tropical buildings. Leveraging the capability of WSN, illuminance level across the workplane can be collected nonintrusively. Furthermore, weather conditions, hence the amount of available daylight, and occupant activities can also be assimilated into the system, which can subsequently optimize the building operations so as to improve the energy efficiency and occupants' satfisfaction, visual comfort in particular.

The remainder of the paper is organized as follows. In Section II, recent research efforts on light monitoring and control are reviewed. Features of the proposed system and its implementation are described in detail in Section III and IV respectively. Experience learned during our system development and further issues are discussed in Section V. Finally, Section VI provides the concluding remarks.

II. Related works

Minimizing power consumption by controlling the dimming level of a LED lighting system is investigated in [5]. The problem is formulated as a constrained LP problem, which tries to provide a uniform illumination around an occupant while at the same time maintains a minimum level of illumination over the whole workplane. Illumination levels are, however, not obtained from direct measurements but estimated using Lambertian function. An extension work [6] considers local sensing and control in a networked LED-based lighting system. Allowing some information exchange within a neighborhood, a distributed LP problem formulation ensues.

Daylight-responsive dimming systems can reduce the power consumption of electrical lighting by introducing daylight. For instance, a heuristic is proposed in [7] for a light control system via CAN-bus. In order to reduce the electricity consumption by harvesting daylight, the system continuously adjusts the opening angle of the venetian blinds and intensity of electrical light in two separate steps, by comparing the difference between indoor and outdoor illuminance levels and the user preference. In [8], Park et. al integrates information such as roller shade height and exterior global irradiance into a closed-loop proportional control algorithm developed earlier in [9].

With the recent development in wireless sensing technology, WSNs are frequently used for lighting control system. A WSN-based intelligent light control system is proposed in [10] to satisfy each user's illumination requirement, which is defined as a combination of background and local illuminance levels. Two user requirement models, namely binary and continuous satisfaction models, are considered. The light adjustment problem for the former model can be formulated as a LP problem, while the continuous satisfaction model leads to a NLP problem. Assuming the local lighting has limited effect on the background illuminance level, the problem can be solved by 2-stage optimization to minimize the power consumption.

An intelligent LED lighting system is presented in [11]. It consists of multiple sensor nodes, each of which integrates a motion sensor, an illumination sensor and a ZigBee module. Users are required to input their feedback via smart phones so that the system parameter (i.e. minimum light intensity) are adjusted automatically.

In [12], the authors employ WSN to allow for personal control of a DC-grid powered and DALI-based LED system in a windowless office. In each personal workspace, a light sensor and a LED complete a close loop control that adjusts the illuminance level to suit the user preference in real-time.

III. System Architecture

The proposed system currently consists of a WSN-based monitoring system, a database, a web interface, and a controller for lighting and blind, as portrayed in Fig. 1. Indoor environment data, such as illuminance level, temperature and occupancy, are first collected by the sensor nodes and forwarded to the base station. The data are then decoded and stored in the database. Real-time and historical data can be displayed in the web interface, or are used for further analyses. Some intelligent control algorithms residing on the server are responsible for issuing control commands to the controller, which changes the states of the luminaires and window blind accordingly.

IV. Prototypical Implementation

This section describes the testbed we developed, along with a detailed description of the corresponding hardware and software components.

A. Testbed Description

For rapid system validation and verification, we decided to implement the proposed system in a mock-up, which is built after a typical faculty office in NTU. The dimensions of the selected office are 5.97m (L) x 2.85m (W) x 2.63m (H), with its configuration illustrated in Fig. 2a.

The mock-up is built in a 1:7.5 scale, and is made out of plywood of 12mm thickness to give a sturdy structure. Styrofoam board is installed onto the ceiling to represent the false ceiling. It also serves as a compartment to house the wires, LED luminaires and ceiling-mounted occupancy sensors. Two strips of LED are attached on the false ceiling to represent the luminaires in the office, as shown in Fig. 2b.

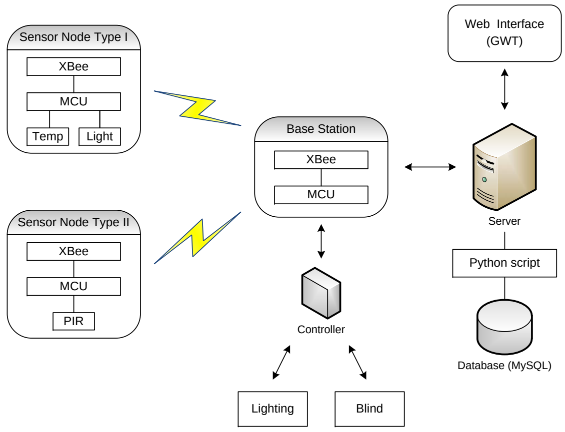


Fig. 1. System architecture of the proposed WSN-based intelligent visual performance management system.

A piece of transparent acrylic is mounted on the window to simulate the glass window in the actual office. In order to mimic the daylight entering the mock-up office, a LED lamp is erected outside and facing the window. The neck of the lamp is movable in order to simulate different solar positions and angles. A roller blind made of fabric is fitted to the window for controlling the amount of admitted "daylight".

B. WSN-based Monitoring System

The monitoring system is built on Arduino. Arduino is an open-source platform for prototyping, hence it is easy to customize according to our needs with minimal cost. Each Arduino board is equipped with a Digi's XBee module for wireless communications. These modules are IEEE 802.15.4-compliant and can communicate with each other at 2.4GHz.

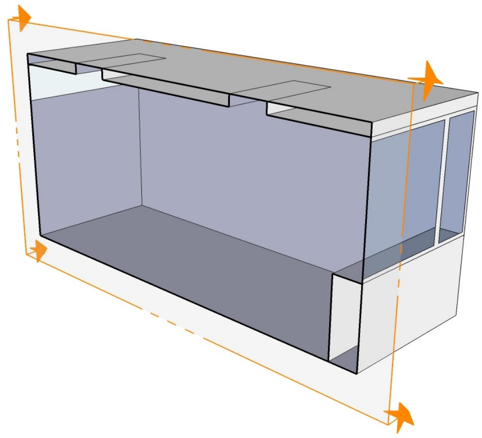
We use an Arduino UNO and an XBee module with a wireless shield to implement the base station, which acts as a gateway between the WSN and the rest of the system.

Arduino Fio is selected to build the sensor nodes, primarily due to its small form factor. It operates at 3.3V and offers a number of analog and digital I/O pins. A built-in socket is available for the XBee module.

Two types of sensor nodes are developed in the project. Type I sensor node is equipped with an illuminance sensor and a temperature sensor. These sensors are deployed over the workplane for light and temperature sensing. Type II sensor node is equipped with an occupancy sensor and is normally mounted on the ceiling to detect user's presence.

The following sensors are selected for the sensor nodes:

1) Occupancy Sensors: To detect the presence of occupant, we use a passive infrared (PIR) sensor to detect any motion. A digital infrared motion sensor, SEN0018, is selected for this purpose. It operates with a 3–5V supply, suitable for Arduino Fio. Preliminary test of the sensor shows good response to motion. It registers a 100% catch when the movement occurs within 2m from the sensor and only reduces to 90% for 3m.



(a)

(b)

Fig. 2. Modeling after a typical faculty office in NTU: (a) sectional view and (b) image showing the interior of the mock-up with LED luminaires, motorized roller blinds and both types of wireless sensor nodes.

2) Temperature Sensors: LM35 is chosen because it requires a low supply voltage and provides high reading accuracy ($\pm 0.5\,^{\circ}$C). Although the required minimum operating voltage is 4V, our test shows that at 3.3V (Fio operating voltage), it still produces comparable results.

3) Illuminance Sensors: A NPN phototransistor, TEPT5700, is used to measure the ambient illuminance level. It has a spectral bandwidth ranging from 440nm to 800nm, well suited for visible light. Also it has a wide angle of half sensitivity of $\pm 50\,^{\circ}$. Calibration of the sensor is performed with a high precision lux meter (Gossen Mavolux 5032B).

C. Controller

A controller box is installed for the mock-up to control the LEDs and the blind. The controller is implemented on an Arduino Uno with an XBee module attached via a wireless shield. Power is supplied through an AC-DC 12V adaptor. A TIP120 NPN transistor is used to drive the 12V LEDs and allows the Arduino to control dimming level of the LEDs through pulse width modulation (PWM). The roller blind is controlled by a 12V stepper motor, which is in turn driven by a SN754410NE quadruple half-H driver. With it, the Arduino can control the speed and direction of rotation of the motor through four of its digital pins.

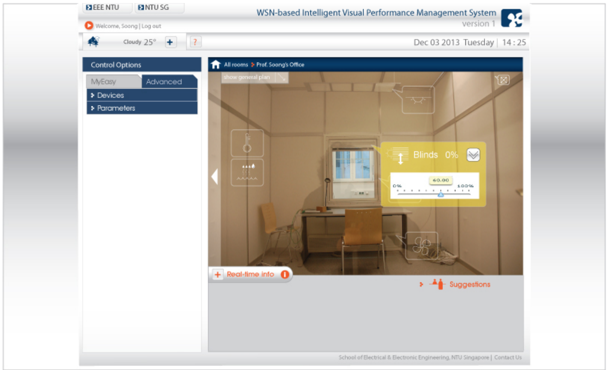


Fig. 3. A sample screenshot of the information dashboard showing the control of the blind. Real-time sensor measurement data can also be displayed.

D. Database

Currently illuminance level, temperature and occupancy data are collected in the mock-up. These continuous data stream require a reliable database for storage. In this phase, the database is implemented in MySQL. Upon receiving a data packet, the base station sends it to the server via serial port. A Python script then decodes the packet and forwards the information to the database. The new data is subsequently inserted into the information database.

Stored data can be later retrieved and displayed on the information dashboard. Further analyses on the data are required to improve control algorithm in a wider deployment of the system.

E. Information Dashboard

A well-designed information dashboard provides a clear and efficient interface for information exchange between the system and users. Via this dashboard, measurement data are displayed and control commands are to be issued by users.

We opt for a web-based dashboard so that the information can be made readily available as long as one can access the Internet. The dashboard is built using Google Web Toolkits (GWT) on Eclipse 3.6 Helios. GWT is an open source web development toolkit in Java. Data are retrieved from the MySQL database with Remote Procedure Call (RPC). With an image of the office on the background, real-time data such as illuminance level and temperature are overlaid at the exact location of measurement.

A user-friendly control interface is also developed on the dashboard. As shown in Fig. 3, a user can remotely operate the blind from 0% (fully open) to 100% (fully closed). Similarly the LEDs can be dimmed from 100% (full brightness) down to 0% (off).

V. Discussions

Although the work presented here is only for the first phase of the project, a few problems have been encountered during the implementation. For instance, the serial port, by default, is reserved exclusively for the XBee when it is plugged directly into an Arduino board. This poses a problem for the base station as it can no longer connect with the server. A workaround is to configure the XBee to use a software serial via two digital pins, thus leaving the original serial port for communication with the server.

As the light source of our system (i.e. LEDs) is driven by PWM, the illuminance sensor registers a series of fluctuating measurements. Data processing techniques are required to mitigate this problem. We decide to take the average of 1000 samples at the sensor node as the actual illuminance level. Compared to averaging on the server, this choice can save a lot more battery power from unnecessary data transmissions.

In the next phase when the system is deployed in a real physical office, commercial luminaires and blinds will be used. Typically they are compliant with some industrial standards, e.g. DALI. Interfacing (both hardware and software) these products with our control system will entail more sophisticated implementation and vigorous testing. Furthermore sensing domain of the system will be extended to weather conditions. The real-time local weather information can be, for example, obtained by roof-top weather station. With all the necessary data collected and analyzed, an intelligent strategy for building operations is possible to enhance visual performance.

The third phase will see us deploying the system in a larger scale, perhaps covering the entire building. The system can also be extended to measuring other parameters such as humidity and CO_2 concentration. In other words, a real system deployment will involve a large number of sensor nodes, and hence collect a large volume of data. This so-called big data may present a scalability issue to the MySQL database. We are planning to migrate to Cassandra and employing a cluster of remote servers to cope with the problem.

VI. Conclusion & Future Work

This paper presents the preliminary development of a WSN-based visual performance monitoring and control system in buildings. We first introduce the architecture of our proposed system. A WSN is developed to capture real-time measurements for illuminance, temperature and occupancy. The data are stored in a database and displayed on an information dashboard. In this phase, a mock-up (scale: 1:7.5) of a real physical office, along with dimmable LEDs and roller blinds, is also built to demonstrate the functionality of this system.

Currently, an advanced visual performance management system (involving lighting and shading domain), as well as the corresponding mathematical model for optimizing building operations, is being developed. It will be further deployed in an existing open plan office for validating and fine-tuning. In addition, systematic (long-term and high resolution) environmental and occupancy data will be collected for further analyses and improvement of the system. This work will contribute to the intelligent techniques in the visual environment control domain. Moreover, the findings of this research will help to enhance the visual performance and the energy efficiency of buildings in the Tropics.

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