Short Paper: The Smart Conference Room: An Integrated System Testbed for Efficient, Occupancy-Aware Lighting Control

Sina Afshari
Rensselaer Polytechnic Institute
Troy, NY, USA
afshas@rpi.edu

Tianna-Kaye Woodstock
Rensselaer Polytechnic Institute
Troy, NY, USA
woodst@rpi.edu

M.H. Toufiq Imam
Rensselaer Polytechnic Institute
Troy, NY, USA
imamm@rpi.edu

Sandipan Mishra
Rensselaer Polytechnic Institute
Troy, NY, USA
mishrs2@rpi.edu

Arthur C. Sanderson
Rensselaer Polytechnic Institute
Troy, NY, USA
sandea@rpi.edu

Richard J. Radke
Rensselaer Polytechnic Institute
Troy, NY, USA
rjradke@ecse.rpi.edu

ABSTRACT

A key challenge to lighting testbed development is the design of system architecture, both in terms of hardware and software, that supports the exploration of transformative systems concepts. Here, we introduce the Smart Conference Room (SCR) at the NSF Engineering Research Center for Smart Lighting. This regularly-used room combines multi-channel solid state light sources, advanced sensors, and sophisticated control algorithms to provide efficient and comfortable lighting where and when it is needed. We specifically discuss two interrelated sensing and control systems in the SCR. The first uses a sparse network of single-pixel color sensors for closed-loop feedback control of the light field in the room, driving the light field to a desired setpoint while harvesting incoming daylight and balancing energy costs. The second uses a low-resolution array of time-of-flight sensors to track occupants, identify their behavior, and trigger lighting modes, all while preserving their privacy. We describe ongoing and future experiments in the SCR that drive the specifications and development of new sensors, sources, and advanced control algorithms.

Categories and Subject Descriptors

C.2.4 [**Computer-Communication Networks**]: Distributed Systems; H.4.1 [**Information Systems Applications**]: Office Automation; I.4.6 [**Image Processing and Computer Vision**]: Segmentation

Keywords

Smart Lighting; Daylight Harvesting; Occupancy Tracking; Activity Modeling

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1. INTRODUCTION

The U.S. Department of Energy estimated that in 2011, 41% of total energy and 73% of U.S. electricity was consumed by building energy use. In addition, building energy use is dominated by lighting, heating, and cooling, with lighting (20%) the largest use of energy in commercial buildings [6]. Major savings of lighting energy (40-60%) can be achieved by the application of lighting control strategies including vacancy detection, dimming with daylight, demand response, and personal controls. At the same time, the goals of lighting design for both commercial and residential buildings have recently shifted from "visibility" — simply providing necessary illumination for occupant functions — to "lighting quality", which encompasses a broader range of considerations including occupant health, productivity, and comfort. The exploration of these diverse factors requires the development of new types of testbed facilities with functionality and infrastructure that support new concepts and encourage the systematic evaluation of innovative ideas and systems approaches.

In this paper, we introduce the Smart Conference Room (SCR), a full-scale, regularly-used testbed in the Smart Lighting Engineering Research Center at Rensselaer Polytechnic Institute, which enables the development and demonstration of sophisticated lighting control algorithms. The SCR features multi-channel light sources with adjustable intensity and spectral distribution, sparse networks of ceiling-mounted color and distance sensors to estimate the light field and occupancy of the room in real time, advanced feedback control algorithms to drive the light field to a desired state, and a flexible network architecture to handle the diverse input and output signals from the sources, sensors, and controls. The system harvests incoming daylight, maintaining a desired lighting setpoint while reducing energy costs, and can automatically trigger different target light fields based on the identified activities, all while maintaining the privacy of the room's occupants.

The system-level vision of the Smart Conference Room is illustrated in Figure 1, which shows the interconnections between the lighting sources, multi-modal sensors, and ad-

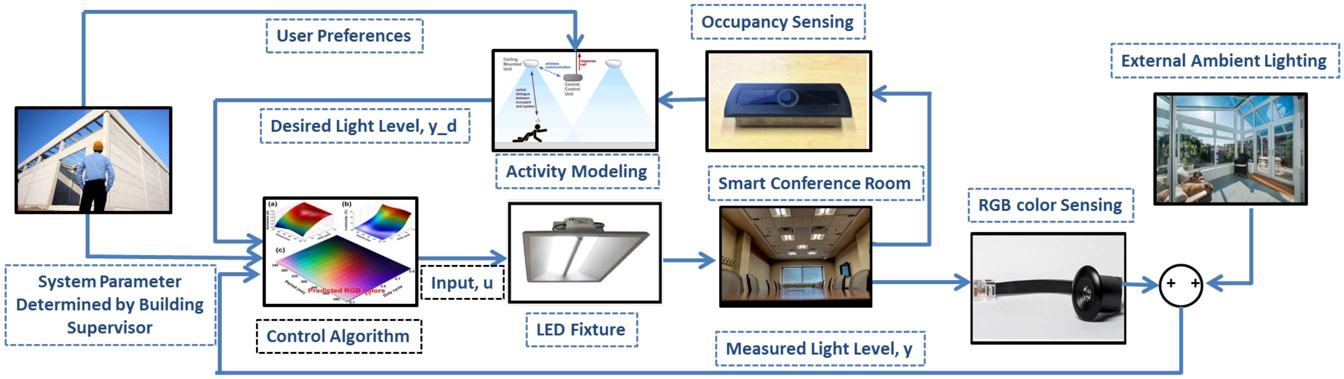


Figure 1: The systems-level vision of the Smart Conference Room.

vanced control algorithms. This vision represents the first step in the overall control of the light field, or plenoptic function, in the room: that is, the time- and wavelength-dependent distribution of light intensity at each viewer location and gaze angle.

2. TESTBED INFRASTRUCTURE

The Smart Conference Room (SCR) is a $11' \times 28'$ furnished conference room, located on the campus of Rensselaer Polytechnic Institute (RPI) in Troy, New York, USA. This is a fully-functioning conference room, used for meetings, presentations, and other official gatherings. At the same time, it serves as one of the most advanced experimental testbeds of the NSF Smart Lighting Engineering Research Center, enabling the development of advanced sensing and feedback control for lighting systems, as well as human factors tests. The room is equipped with ten 5-channel color-tunable light fixtures. Fifty-three single-pixel RGB (red, green, blue) downward-pointed color sensors are installed in the ceiling, one per 2'×2' tile. Eighteen time-of-flight sensors are also installed in the ceiling for occupancy detection, localization, and activity recognition algorithm development. The room has windows on the eastern and northern walls, allowing natural daylight to serve as ambient external light. Figure 2 illustrates the SCR and the layout of its different components.

Figure 2: The Smart Conference Room at Rensselaer. The black dots in the ceiling tiles are RGB color sensors, and the black bars are infrared time-of-flight sensors.

2.1 LED Fixtures

The color-tunable light fixtures installed in the testbed employ Telelumen light engines retrofitted in Cree troffers. Each of the fixtures has five LED color channels (red, green, blue, amber, and phosphor-converted white), allowing for high-quality color rendering and a wide array of color generation within the room. Each fixture is connected to a Raspberry Pi processor board that allows for individual and independent communication during system operation.

2.2 RGB Color Sensors

Each color sensor module consists of a TCS34725 sensor chip from AMS-TAOS. These sensors have a dynamic range of lux measurement, very short response time, and fine angular resolution. A particularly appealing feature of this sensor is the integrated IR blocking filter, ideal for sensing ambient lighting in the visible spectrum. To improve the color measurement and reduce the integration time (which is normally 100ms), we incorporated an optical lens from Carclo Optics into each sensor. These are total-internal-reflection (TIR) narrow-beam lenses that focus the incident light on the sensor chip. Each sensor-lens pair is integrated with an acrylic mount that allows the sensor module to be installed in the ceiling of the testbed. The angular sensitivity of these sensor modules was measured as approximately 18°. Each RGB sensor is highly energy efficient, consuming about 5mW each.

All fifty-three sensors are connected to a single Raspberry Pi computer through an 8×8 multiplexer, making the system less cumbersome and reducing the number of hardware components. The Raspberry Pis used to control the fixtures and sensors are connected to a main computer via a local Ethernet connection. At every time step of the control loop, the sensors send the measured data to the main computer, where the control input for the next time step is calculated and sent to the light fixtures.

2.3 Time-of-Flight Sensors

The sensors used for occupancy detection are based on time-of-flight technology, analyzing the phase difference between emitted and reflected infrared signals to estimate the relative distance of an object from the sensor. These IRMA Matrix sensors, designed by Infrared Intelligent Systems (iris), were originally designed for automatic passenger counting in buses and trains. We repurposed them for gathering occupant information necessary for lighting control in a smart space. These sensors operate in the near infrared range of the electromagnetic spectrum (≈850nm) allowing for the constant emission of light invisible to the naked human eye. The sensors have a detection range of 5m with an accuracy of 1cm. They operate at a frame rate of 40fps with a beam angle of 52°×40° and a resolution of 25×20 pixels. The time-of-flight sensors are mounted on the ceiling pointed downwards and are connected via ethernet to the main PC.

The time-of-flight based occupancy detection system is described more fully in Jia and Radke [5], which discusses how occupants can be located in a room to within several centimeters in real time, distinguished from furniture, and classified into coarse poses (standing, sitting, lying down), all while maintaining the occupants' privacy. Figure 3 illustrates an example snapshot of the algorithm.[1].

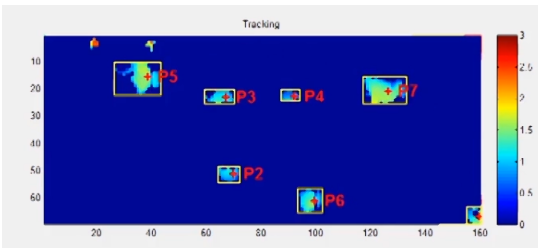


Figure 3: Results of occupancy tracking algorithm.

2.4 Networking Configuration

The sensors and light sources installed in the SCR are generally consumer products that have been modified to support the development of lighting control algorithms. Unfortunately, many of the systems use different communication protocols, making the interfacing and development of a combined system problematic. To achieve sensor and source communication compatibility, the SCR network is supported by an open source distributed communication and control software system, Robot Raconteur, originally developed at Rensselaer Polytechnic Institute in support of robotics research [8]. Robot Raconteur makes it easy for disparate sources, sensors, and control algorithms written in different programming languages to communicate, without requiring the development of translators or custom communication protocols.

3. LIGHTING FEEDBACK CONTROL

3.1 Problem Formulation

In a typical lighting control system, the input to the controller is the set of individual control signals to the different fixtures, and the output is the measurement from the sensors. In a space with n light fixtures, each containing p LED channels, the input vector $u^i \in \mathbb{R}^p$, $i = 1, 2, ..., n$. Thus, we have in total pn control variables each of which is constrained to lie in $[0, 1]$, indexing the minimum and maximum light intensity settings.

Assuming there are m sensors each having q color channels, we have qm entries in the measured output vector $y^j \in \mathbb{R}^q$, $i = 1, 2, ..., m$. If the responsivity function for each sensor is $C^j(r, \theta, \lambda) \in \mathbb{R}^q$, the output at each location is thus given by $y^j = \langle C^j, \phi \rangle + v^j$ where $\langle ., . \rangle$ denotes integration over the spatial, angular, and spectral ranges of the color sensor, ϕ is the light field in the room, and v^j is the sensor noise [1]. The input-output relationship for the lighting system can be modeled by the *light transport model* $y = Gu + w + v$, where $y = [y^1, y^2, \cdots, y^m]^T \in \mathbb{R}^{qm}$ is the output light measurement vector, $u = [u^1, u^2, \cdots, u^n]^T \in \mathbb{R}^{pn}$ is the light intensity control vector, $G \in \mathbb{R}^{qm \times pn}$ is the *light transport matrix* [4], $w \in \mathbb{R}^{qm}$ is the external ambient light measured by the sensors, and $v \in \mathbb{R}^{qm}$ is the measurement noise vector. G can be obtained for a given illuminated space from experimental input-output data using a least-squares fit. A more detailed description of the method can be found in [2].

In general, the control problem for lighting systems can be formulated as in [1, 2]:

$$\begin{aligned} \underset{u}{\text{minimize}} \quad & J = \mu_Q(\phi^{des}, \phi(\psi), u) + \alpha_u \mu_E(u) \\ \text{subject to} \quad & \mathbb{F}(u, \phi(\psi)) \in \mathbb{S} \end{aligned} \tag{1}$$

where ϕ^{des} is the desired light field, $\phi(\psi)$ is the light field in the room from external ambient light ψ, μ_Q is a metric defining the quality of the total light field compared to the desired light field, α_u is an adjustable weighting coefficient determining the relative cost between comfort and energy consumption, and μ_E is a metric representing the power consumed by the light fixtures. The function $\mathbb{F}$ and the set $\mathbb{S}$ define the constraints on the optimization and can be used to model actuator saturation, human comfort requirements, and so on. Since ψ is unknown and time-varying, feedback methods are necessary to solve (1) online.[2] As in [2] it is assumed that ϕ^{des} is given based on pre-determined comfortable lighting scenarios. The control update law can then be designed as a gradient (or Newton-Raphson) descent step, details of which can be found in [1].

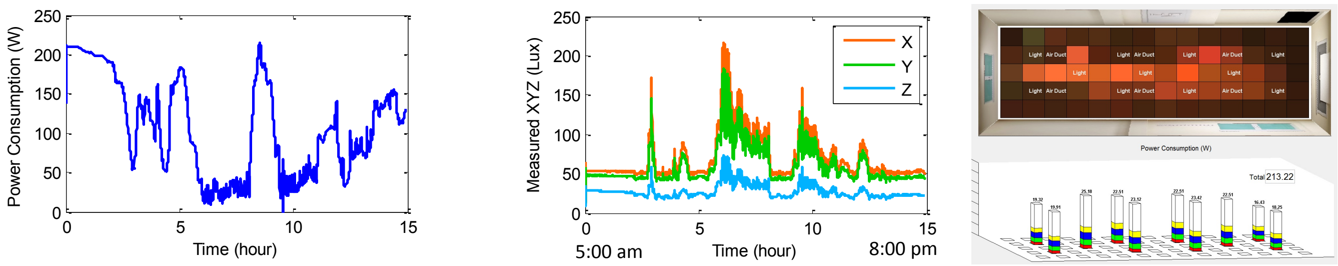
3.2 Full-Day Performance Experiment

We describe one full-day experiment in the Smart Conference Room in which the daylight harvesting aspect of the system is illustrated. The desired light field for this experiment was specified as $CCT = 4300K$, with a minimum of 450 lux on the conference room table. The test started at 5:00 am and ended at 8:00 pm on 06/23/2015.

The resulting power consumption and sensor measurements are shown in Figure 4a–b. The power consumption was observed to be larger at the beginning and the end of the experiment. This indicates that before sunrise and after sunset, the system consumed larger electrical power to maintain the desired light field. On the other hand, during the daytime hours, the incoming daylight from the windows was harvested by the controller to illuminate the space, resulting in smaller values of power consumption as shown in Figure 4a. Figure 4b shows that at certain points of time during the day, the incoming daylight resulted in sensor measurements larger than the desired values. That is, for large amounts of incoming daylight, it was not possible to eliminate the effect of disturbance by dimming the fixtures (source saturation). While the controller used the raw RGB values from the sensors, the sensor readings for this experiment

[1]A short video clip illustrating real-time ToF-based occupancy tracking in the SCR is available at `https://www.youtube.com/watch?v=ToRbsfxxiCY`

[2]A short video clip illustrating real-time light field control in the SCR is available at `https://www.youtube.com/watch?v=UKufEmoaJUs`



(a) (b) (c)

Figure 4: (a) The total power consumption in the full-day feedback control experiment. (b) Sensor measurements for a sample sensor in the XYZ color space. (c) The graphical user interface developed to monitor the experiments.

were converted to and presented in the XYZ color space, since these are often of more significance for lighting applications. The average power consumption for the full day was 111.80W, which represented a 49 percent saving compared to the average power consumption required for the desired lighting condition, 220W. The real-time graphical user interface developed in MATLAB to monitor the experiments is illustrated in Figure 4c. The top image shows a pixelated top-down view of the SCR and the bottom graph illustrates the power consumption for individual channels in each of the light sources.

4. DISCUSSION AND FUTURE WORK

One difficulty with comparing lighting feedback control algorithms from the literature is that they are implemented and evaluated in testbeds of various sizes and configurations. An ongoing effort in the SCR is to implement several previously proposed algorithms so that direct comparisons and recommendations can be made. We are also investigating additional parametric studies by varying lighting parameters such as illumination or CRI. We are also extremely interested in investigating human comfort factor aspects of light field control in the SCR, which opens a wide range of opportunities for human behavioral studies.

In terms of real-time occupancy sensing, we are currently investigating more advanced pattern recognition algorithms, such as dynamic clustering and neural networks, to better estimate occupancy patterns and select light fields that are appropriate and effective. We are also currently evaluating arrays of single-pixel time-of-flight sensors, which would match the currently deployed single-pixel color sensors.

We are particularly interested to investigate multisensor fusion of the color and ToF modalities in the SCR to interpret room activities and adaptively guide lighting control. For example, the ToF sensors provide object distance information and are complementary to the installed color sensor array that provides spectral distribution of reflected light patterns. Previous work [7] demonstrated the feasibility of using imperceptibly-modulated light in combination with sparse color sensors to estimate configurations of objects in a smart room. We also plan to integrate finer-level classification of human gestures for smart lighting applications, using machine-learning algorithms applied to very-low-pixel-count sensors [3].

More broadly, we hope to integrate other aspects of building system sensing and control into the SCR, such as actuation of window blinds and the HVAC system based on occupant behavior.

5. ACKNOWLEDGMENTS

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