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Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy in California Buildings

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Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy in California Buildings

California Energy Commission

Gavin Newsom, Governor

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DISCLAIMER

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy In California Buildings is the final project report for Contract Number EPC-14-017 conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's EPIC Program.

All figures and tables are the work of the author(s) for this project unless otherwise cited or credited.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

An important strategy to meet California's ambitious energy efficiency goals is to use innovative wireless communications, embedded sensors, data analytics and controls to significantly reduce lighting energy use in commercial buildings. This project developed a suite of networked lighting solutions to further this goal. The technologies include a platform for low-cost sensing, distributed intelligence and communications, the “PermaMote,” which is a self-powered sensor and controller for lighting applications. The project team also developed a task ambient daylighting system that integrates sensors with data-driven daylighting control using an open communication interface, called the “Readings-At-Desk” (RAD) system. To address the problem of building occupants being confused about how to operate traditional lighting control systems, the research team created content that could be the basis for a user interface standard for lighting controls. Finally, to address the difficulty of ensuring that advanced lighting control systems actually deliver their promised energy savings, the project team developed a new method for evaluating and specifying lighting systems' performance.

The research team validated these technologies in the laboratory, showing significant lighting energy savings, up to 73% for the PermaMote sensor system from occupancy control and daylight dimming features, compared to the same light source (LED replacement lamps) operated via simple on/off scheduling. The project team also developed a proposed standard lighting data model and user interface elements, which were contributed to the ANSI Lighting Systems Committee (C137) for standardization. Existing data models are incomplete and inconsistent, whereas the lighting-specific data model developed here is clear and comprehensive, to serve as a starting point for creating common, universally agreed upon semantic definitions of key lighting parameters, to promote interoperability. For the task on verifiable performance of lighting systems, the project team developed a more effective metric for capturing the actual energy impact of a lighting system over time — the energy usage intensity (kWh/ft2/year). Three commercial lighting systems were tested in FLEXLAB® using this new metric, and the tests show a wide range in the accuracy of the self-reported energy-use metric, from 0.5% to 28% error compared to direct measurement of lighting energy using dedicated submeters. Overall, the project team estimates that these advanced technologies can reduce California office lighting energy use by 20% (above and beyond normal advanced lighting controls mandated by Title 24), resulting in about 1,600 GWh/year in savings.

Keywords: Wireless Communications, Networked Lighting Controls, Embedded Sensors, Standard User Interface, Lighting System Performance, Task Ambient Lighting Integration

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Executive Summary

Introduction

California Senate Bill 350 requires that the state's energy-efficiency savings double by 2030. One strategy toward meeting that goal is to use new technologies to greatly reduce electricity use while maintaining or improving building system and end-use performance. Commercial buildings account for more than a third of the energy used in California, and lighting is the largest end-use in these buildings. With the advances in information and communication technology over the last several decades, there are now a wide range of innovative wireless communications, embedded sensors, data analytics and controls that offer substantial opportunities to optimize building systems in real time to reduce energy use.

To take advantage of these technologies, lighting systems need to evolve to:

1. Channel new entrants in the lighting market to address energy usage,
2. Harness innovation in the Internet of Things (IoT) sector,
3. Respond to the needs of the utility grid to enable buildings as a flexible loads, and
4. Address entirely new lighting services, e.g., circadian lighting, that are making the lighting market more complex.

Several shortcomings are keeping lighting systems from realizing their energy saving potential. Traditional lighting systems lack "awareness," which leads to inefficiency and suboptimal performance. For buildings that do have advanced lighting control systems, the increasing complexity of these systems leads to user confusion. Finally, dynamic and customized control capability in new lighting systems makes it hard to specify and verify energy performance.

A Suite of Networked Lighting Solutions

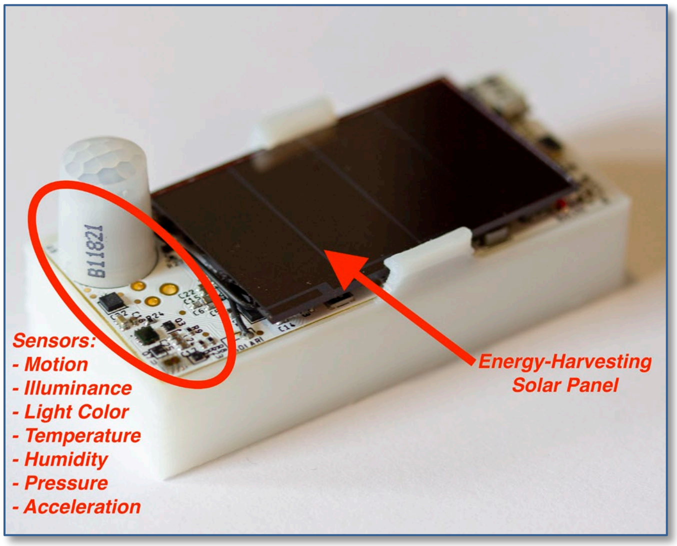
The purpose of this project was to apply the information and communication technology advances described above to address the shortcomings of traditional lighting control systems. The research was conducted in three main areas detailed in the following sections:

1. Sensor-rich Networked Lighting Systems
2. Intuitive, Standardized User Interfaces for Networked Lighting Systems
3. Verifiable Performance for Networked Lighting Systems

Sensor-rich Networked Lighting Systems

The project team developed a low-cost sensing, distributed intelligence and communications platform, the "PermaMote," which is a self-powered sensor and controller for lighting applications. The PermaMote includes multiple sensor types (e.g., light level, light color, motion, temperature, humidity) as well as energy harvesting capability, contained in a small and light form factor, and using industry-standard networking protocols.

Figure ES-1: PermaMote Design



Sensors for environmental factors like temperature and RH provide the opportunity for optional future integration into HVAC control, and lighting color information can be processed into correlated color temperature (CCT) for spectral tuning, which some solid-state lighting systems allow. The simple, low-cost, wireless multi-sensor platform allows dense distribution of sensors in the controlled space, providing rich spatial coverage for the measured attributes. The platform also implements a new reference lighting data model, for improved interoperability with other lighting systems.

The project team also developed an effective task ambient daylighting system that integrates sensors with data-driven daylighting control using an open Application Programming Interface (API – a set of definitions, communication protocols, and tools for programming and communication). This technology, the "Readings-At-Desk" (RAD) system, uses illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights. The RAD sensors located at the desktop easily integrate with commercially available Zigbee[1]-controllable lamps and luminaires for a low-cost networked lighting control retrofit.

[1] Zigbee is an IEEE 802.15.4-based specification for wireless communication in personal area networks, It is intended for low-power operation in applications such as home automation, medical devices, and other low-power low-bandwidth needs. Zigbee includes the entire network stack from physical to application layers. (Source: Zigbee Alliance)

Figure ES-2: Task Light Version of RAD Controller

Intuitive, Standardized User Interfaces for Networked Lighting Systems

To address the problem that many modern lighting systems are confusing for building occupants to understand and operate, the research team created content to serve as the basis for a user interface standard for lighting controls. The content included standard terms, symbols, and colors to help humans more effectively control lighting systems. The User Interface Standard creates a consistent language for lighting control covering both basic and advanced capabilities and should influence the design of future lighting controls.

Verifiable Performance for Networked Lighting Systems

To address the difficulty of ensuring that advanced lighting control systems actually deliver their promised energy savings, the project team developed a new method for evaluating and specifying lighting systems' performance. This involved developing a set of evaluative metrics, and reviewing current technologies for their ability to offer this information. The evaluation metric (lighting energy over time per unit area, or kWh/ft2/year) allowed for comparison of measured lighting energy intensity to the lighting energy as reported by commercial technologies with energy reporting features to assess accuracy of reporting methodologies.

Key Innovations

This project took advantage of advances in low-cost sensors, wireless communication, computation, and data storage to deliver these innovations:

1. Energy harvesting sensors and open communication
    - Allows for autonomous placement of sensors throughout space in dense yet cost-effective networks, reliable operation over time (no battery changes) and seamless communication via open protocol with controlled endpoints.
2. Desktop-based daylight sensing and control

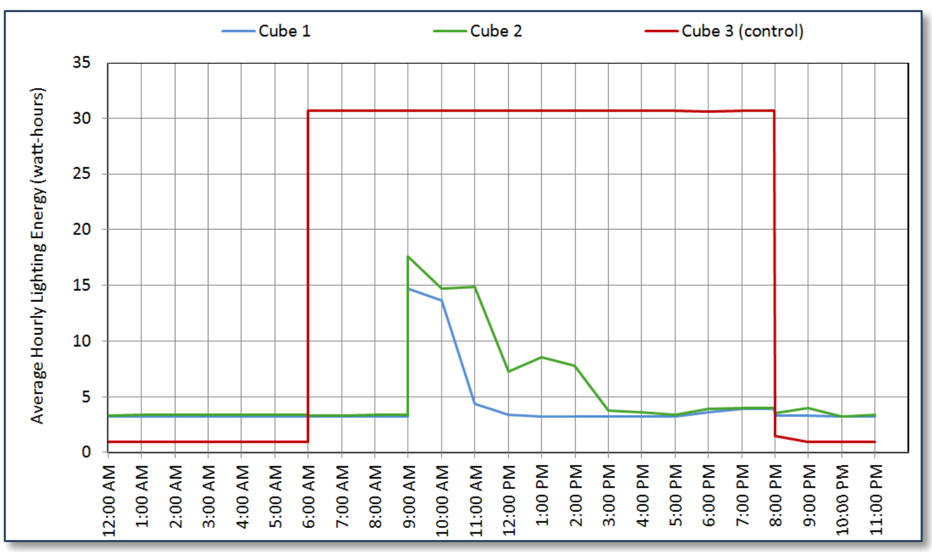
- Desktop light measurement more accurately characterizes the light levels that matter for users (compared to ceiling-based measurements) and wireless sensor architecture allows sensor to be situated and moved on desk to prevent it being covered by other items.

3. Intuitive, standardized interface elements for lighting
    - Provides a consistent language for lighting control capabilities, enabling interoperability and competition in the marketplace. Existing data models are tied to specific protocols whereas the proposed data model was developed in collaboration with industry through the ANSI C137 committee and is protocol and vendor neutral.
4. Verification of performance and metrics through Lawrence Berkeley National Laboratory FLEXLAB® testing.
    - Enables comparison of systems' energy reporting accuracy and energy intensity metric provides basis for outcome-based lighting code that focuses on real-world performance rather than installed capacity.

Project Results

For the PermaMote, FLEXLAB® testing showed significant energy saving through occupancy and daylight control, as shown in Figure ES-3. With the occupancy control and daylight dimming features, the experimental offices saved around 73% energy on average during the week-long test.

Figure ES-3: Comparison of average hourly energy consumption across test offices

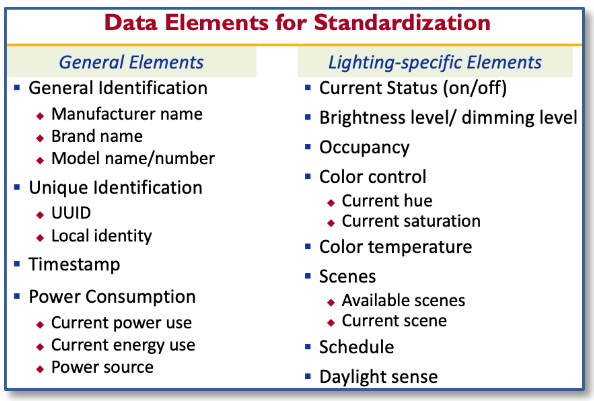


As part of the research to develop an open API, to allow facility managers and owners to extend the reach of wired lighting systems, the research team developed a reference data model that could be used to communicate between existing lighting systems and the PermaMote sensors.

The intent of standardizing the data model is to allow vendor interoperability. The reference data model includes:

- Types of information to be represented for lighting applications (Figure ES-4)
- Specific data elements to include
- Names for those data elements
- Data encoding (units, enumerations, etc.)

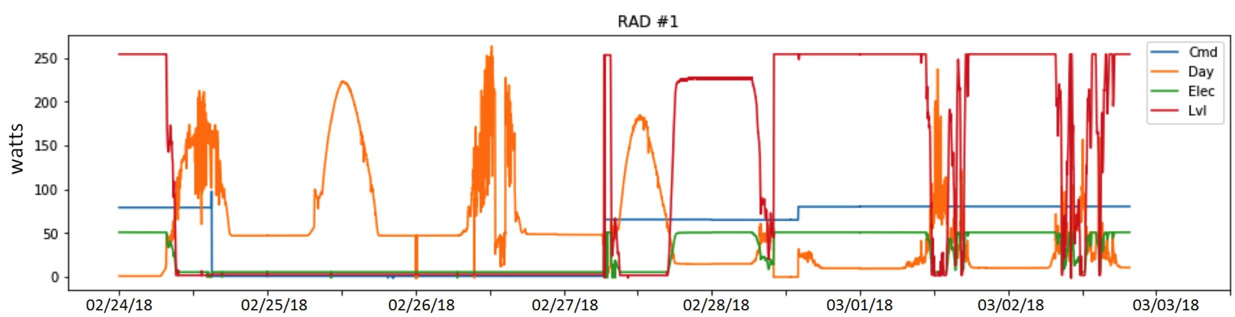
Figure ES-4: Proposed Data Model



In addition to the project team's research, LBNL also engaged with the ANSI Committee C137, which is in the process of creating an ANSI standard for lighting control systems. As part of the committee's work, LBNL participated in the development of a standard data model that will be a part of the eventual standard.

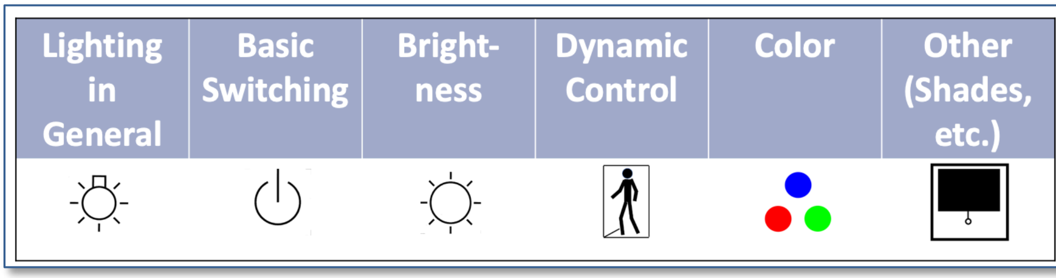
For the RAD controller, FLEXLAB® testing showed significant energy saving through daylight harvesting, and more precise desktop illuminance, as shown in Figure ES-5.

Figure ES-5: Performance of one RAD controller during one week of testing



For the standard user interfaces portion of the task, the project team extensively surveyed and digested the content of user interfaces on products currently for sale. The team then crafted the content for a potential standard (Figure ES-6), and presented it to a suitable standards development organization (SDO). The standards body that was selected was the National Electrical Manufacturers Association (NEMA), which sponsors the ANSI Lighting Systems Committee (C137). LBNL met with the ANSI committee several times throughout 2017 and 2018, and presented the proposed content to the committee. As of the publication date of this report, the ANSI committee is still considering the proposed standard.

Figure ES-6: Lighting User Interface Elements



For the task on verifiable performance of lighting systems, the project team developed a more effective metric for capturing the actual energy impact of a lighting system over time, which is the energy usage intensity ($kWh/ft^2/year$); the typical lighting system metric in building code is simply installed capacity (W/ ft^2), which says nothing about system energy performance over time for systems that are highly controllable and dynamic. The team then developed software to validate the ability of lighting systems to monitor their energy use, for purposes of calculating an Energy Use Intensity (EUI[2]). Three commercially available lighting systems were then tested in FLEXLAB® to compare their energy reporting capabilities (some systems measure energy, with different degrees of accuracy, whereas others calculate energy based on assumptions and lookup tables) to the values measured by FLEXLAB®. Results of this testing are shown in Table ES-1. One observation from this testing is that lighting systems that directly measure their energy use tend to report more accurate data, compared to those that estimate energy use using a model.

Table ES-1: Networked Lighting Control System energy reporting data compared to reference measurements

	Reference Energy Data (Wh/ft^2)	Reported Energy Data (Wh/ft^2)	Daily Error: reported - reference (Wh/ft^2)	Daily Error/ Daily Total (%)
System 1 (calculated)	4.66	5.95	1.29	27.7%
System 2 (measured)	6.10	6.13	0.03	0.5%
System 3 (measured)	9.86	9.07	- 0.78	-7.9%

Benefits to California

Networked lighting controls systems hold the promise of unlocking significant new value by capturing detailed environmental and device level sensory information. They can also implement strategies to reduce energy consumption and manage building lighting load without

[2] Energy Use Intensity (EUI) can be defined as the measured building's annual energy consumption (either in BTU or kWh) relative to its gross area in square footage.

negatively affecting lighting characteristics, such as dim level or color, so that user comfort is unaffected. Overall benefits related to project outcomes include:

- Helping California achieve its policy goal of 60-80% reduction in lighting energy use; an estimated ~1,600 GWh/year statewide savings potential from these solutions (20% incremental savings added to average savings from Title 24-mandated advanced controls of 38%).
- Reducing cost to install and commission advanced lighting controls, targeting existing buildings (AB758).
- Pervasive sensing and control improves occupant satisfaction and productivity.
- Standard user interfaces make lighting systems easier to use and avoid energy waste.
- New performance metrics allow outcome-based codes.

Conclusions and Recommendations

Through this project, promising new networked lighting controls solutions were developed with easily deployable sensor packages for more accurate representation of conditions in the built environment, thereby providing better lighting control. These systems include the low-cost sensing, distributed intelligence and communications platform, the PermaMote, and the Readings-At-Desk (RAD) system, which uses illuminance measured at the desktop to control overhead lights. Functional testing of these systems yielded generally positive results; the technologies controlled lights as intended through the sensor inputs, programming, and wireless protocols used. Field evaluations of both systems also proved their viability in actual occupied office environments. It is expected that these technologies will continue to develop through further research efforts and eventually transition into commercial viability. The project team also developed a reference data model for lighting and engaged with the ANSI Committee C137 for adoption as an industry standard. More work is needed with this committee to adopt the standard data model.

For lighting user interfaces, this project has developed standard content and proposed it to the appropriate body for adoption. The content was derived from extensive analysis of existing user interface standards as well as examination of the controls found on many diverse products in the market. More work is needed to turn this content into a final standard.

With the advent of energy reporting features from many networked lighting control systems, and from the FLEXLAB® study of several systems, the project team found it is possible to track lighting energy outcomes from a new lighting system. If self-reported demand and energy usage from lighting systems is reliably accurate (within an acceptable tolerance), building codes for lighting systems could move from the prescribed lighting-power-density approach to an outcome-based energy usage approach. In general, the measurement-based approach was more reliable and able to address baseline issues, and therefore, preferred for validation purposes.

CHAPTER 1: Introduction

Background

The CA Lighting Action Plan (LAP) calls for 60%–80% lighting energy use reduction by 2020. Additionally, the Lighting Efficiency & Toxics Reduction Act (AB 1109) requires significant reduction in the average statewide electrical energy consumption, from 2007 levels — 50% indoor residential lighting; 25% indoor commercial & outdoor lighting. These laws and policy directives from the state of California are driving urgency of reducing lighting energy consumption.

Project Description

This project advances lighting control system innovation to help realize California's goals. Research, driven by convergence four major trends (below) in commercial buildings is opening a portal to new opportunities to pursue dramatic energy savings through advanced, automated, and intelligent control systems:

- Increased control granularity: An increasing number of building systems are now controllable with a level of discretion that has not before been possible, particularly LED systems that are fully dimmable and individually addressable.
- Increased sensor availability and use: Environmental sensors such as light sensors, occupancy sensors, carbon dioxide (CO_2) sensors, and power meters are becoming less expensive to install in buildings.
- Pervasive communication through wireless networks: Wireless networks are nearly ubiquitous in buildings today. Wi-Fi, Bluetooth, ZigBee and others are increasingly used for building control purposes.
- Low-cost computation: Bundling digital intelligence at the sensors and lights adds virtually no incremental cost. Coupled with communications, this enables interactive, optimized, rule-based control and fault detection systems at very low cost.

This project "Developing Flexible, Networked Lighting Control Systems that Reliably Save Energy" is a comprehensive strategy to make the energy use of all plug loads observable, thereby enabling users to more easily control those loads to save energy, with four technical tasks as follows:

Objectives

- Develop and promote low-cost sensing, distributed intelligence and communications.
- Create an effective task ambient daylighting system integrating sensors with data-driven daylighting control using Open API.
- Develop standard user interface elements for lighting control systems.
- Develop industry-accepted outcome-based lighting system methodologies, metrics and controls testing.

- Target CA's Title 24 Building Energy Efficiency Standards revisions in 2022 to incorporate next generation lighting control systems.
- Identify next generation lighting control systems technology solutions to realize energy savings.
- Work with standards organizations to add capabilities to their protocols.

Project Tasks

- Develop and test ubiquitous, low-cost sensing, distributed intelligence and communications
- Develop and test task ambient daylighting - data-driven daylighting control
- Develop standard user interface elements
- Validate outcome-based lighting systems: methodologies, metrics and controls testing

Anticipated Benefits

- Overall estimated energy savings potential of advanced, networked lighting controls above 20%; equivalent to 1.6 TWh per year for CA, after technologies have been implemented in commercial building stock.
- Result: ratepayers benefit from greater electricity reliability and lower costs by enabling building owners and occupants to better understand, interact and control lighting system energy use.

Smart Lighting Controls Literature Review

Substantial research and development has been conducted to improve lighting controls and controls algorithms. The onset of Internet of Things technologies and networked sensors capabilities has provided controllers with more points to analyze and make decisions on. Singhvi (2005) runs a optimization problem that maximizes the user comfort with respect to the lighting system while using the least energy, demonstrating this using both open-loop and closed-loop control strategies in a small set up with 10 60W lamps and 12 sensor nodes. Rather than built-in occupancy sensors, these used an occupant's RFID tag and similar methods (additional hardware) to detect occupant location. Karapetyan (2018) uses mobile applications and sensors on wearable devices like Google Glasses and smart watches to obtain environment data and control lights in the space. This work tries to minimize energy consumption from fixtures while meeting user-specified requirements, demonstrated by controlling LIFX (https://www.lifx.com/) smart bulbs using sensor measurements from smart phones in a residential environment. The system represents "… a practical application of IoT-based sensing and actuation … for smart lighting control with oblivious mobile sensors, which seeks to induce adaptive continuous control in real-time without complete knowledge of the dynamic uncertain environment."

In a different approach, occupancy and location information is retrieved from the Wi-Fi network by Zou (2018) and this data, in conjunction with user requirements, is used to minimize the energy consumption of all the lights while ensuring that the user requirements are met. This research conducted a 24 week-long test in a commercial space and demonstrated the energy benefit of their algorithm. Koroglu (2014) introduces a distributed illumination balancing algorithm that controls light levels in a space where the zones are not sequestered. The Williams (2012) literature review compiles and compares energy savings findings for the major lighting control strategies deployed in commercial buildings, from occupancy based lighting control, daylight based control, control based on personal preferences and institutional tuning.

Conclusions from a few other research efforts of note to this project's efforts are summarized below:

> Magno (2015) proposes "[a] novel system to control LED lighting with a low cost and low power wireless sensor network ... [which] requires the deployment of complementary sensors with Zigbee radio... experimental results indicate that the proposed system outperforms the state-of-the-art with a significant reduction of power consumption and cost"
>
> Dikel (2018) demonstrated "… substantial energy savings potential (and other potential benefits) associated with a high- resolution sensor network combined with a spatially-defined and granular LED lighting system… networked and solid-state nature of LEDs encourages the co-location of sensors to provide a real-time, high-resolution sensor network. High density of sensors supports more accurate occupancy sensing, permitting substantially shorter timeout periods, and localized daylight harvesting, to ensure that electric lighting is only provided where it is needed, when it is needed, and in the amount it is needed, within zones of a few square meters."
>
> Peruffo (2015) considers "daylight and occupancy adaptive control for a wireless mesh networked lighting system with multiple sensor-equipped luminaires and a central controller. … The light and occupancy sensors respectively determine net average illuminance and occupant presence within their sensor fields-of-view and report these values to a central controller [which] computes dimming levels [via] stand-alone proportional–integral (PI) control law … To make the performance of the lighting system robust to wireless impairments, transmission redundancy and enhancements in the controller are considered. The performance of the proposed system is evaluated for an example open-plan office lighting model under different daylight and occupancy scenarios and a ZigBee wireless network."

Report Organization

Chapter 2 describes the development of low-cost, wireless and energy harvesting sensors that can connect to existing lighting control systems using an open API. These sensors were designed in a way that would allow building owners and managers to extend the reach and capability of already-installed lighting control systems in a simple and cost effective manner. The project also supported further developments and a lab evaluation of an effective task ambient daylighting system that integrates sensors with data-driven daylighting control using an open API. This technology, the "Readings-At-Desk" (RAD) system, uses illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights. The chapter also details the research team's efforts to develop a new reference data model for improved interoperability with other lighting systems that could be used to communicate between existing lighting systems and the developed low cost sensors. The activities leading up to development of the new model (identifying research gaps, listing of topics necessary for a standard data model, examination of existing standards, analyzing them for consistency, coverage, and quality, and recommendations for best practices) are discussed, and the proposed data model is presented, as well as a mapping of the data model elements to lighting controls standard DALI 2.0, currently in development.

Chapter 3 outlines efforts to create content that could be the basis for standardizing user interfaces for networked lighting systems. To address the problem that many modern lighting systems are confusing for building occupants to understand and operate, a user-interface standard could be used by manufacturers in designing products, could be adopted at the U.S. national level, and eventually could be adopted internationally, in order to make products more effective at saving energy. The premise underlying the effort is that consistent controls aid in humans understanding the capability and status of lighting controls they encounter, and being able to most easily express their preferences.

Chapter 4 discusses some of the efforts and challenges related to developing methods for evaluating and specifying lighting systems performance, focusing on energy-reporting capabilities. Examples of outcome-based evaluative metrics are proposed for lighting design and performance that could be validated through lighting controls energy self-reporting. A review of several current technologies for their ability to offer this information is presented, including a quantitative evaluation of the effectiveness of networked lighting systems' energy reporting capabilities to provide outcome-based metrics (energy usage over time, as opposed to prescribed lighting power densities). Energy monitoring from select networked lighting controls systems was validated for accuracy by testing in LBNL's FLEXLAB®.

Chapters 5, 6, and 7 cover technology transfer, benefits to California, and future research direction (respectively). These chapters summarize outcomes of the research efforts toward these ends and provide a picture of where research efforts might be directed in the future to continue progress in developing flexible networked lighting systems that reliably save energy.

CHAPTER 2: Sensor-Rich Networked Lighting Systems

Summary

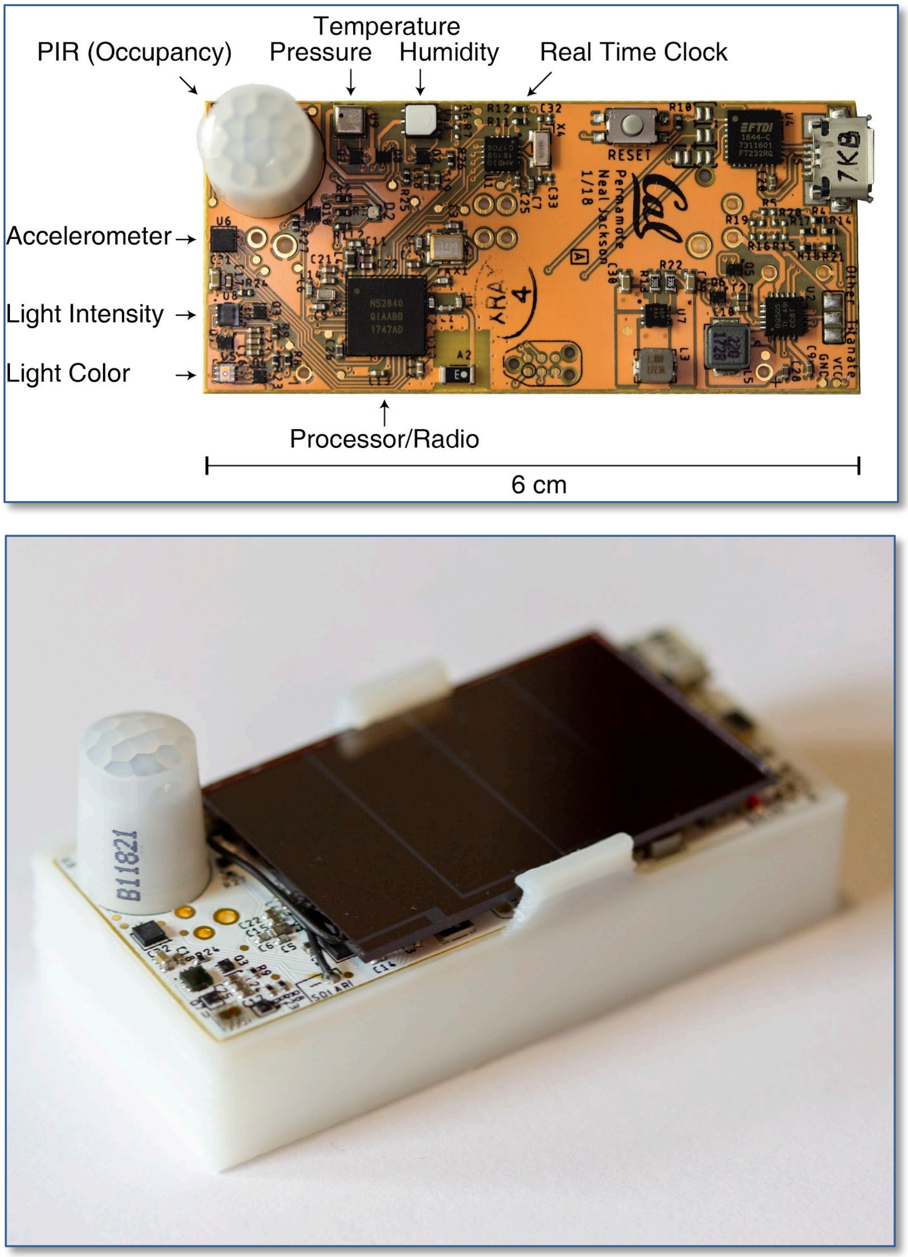
Advanced lighting controls are among the rapidly evolving technologies that utilize wireless communications, embedded sensors, data analytics, and controls to optimize building systems in real time. One of the main project goals was to develop new networked lighting controls solutions with dense sensor packages that could be deployed in the built environment in locations that more accurately represent occupants' experience of the space, thereby providing better control points.

To this end, the project developed a low-cost sensing, distributed intelligence and communications platform, the “PermaMote” self-powered, sensor and controller for lighting applications. The PermaMote includes multiple sensor types (i.e., light level, light color, motion, temperature, humidity, pressure, acceleration, etc.) as well as energy harvesting capability, contained in a small and light form factor, and using industry-standard networking protocols, along with a new reference lighting data model, for improved interoperability with other lighting systems. The project also further supported developing an effective task ambient daylighting system that integrates sensors with data-driven daylighting control using an open API. This technology, the “Readings-At-Desk” (RAD) system, uses illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights. The RAD sensors located at the desktop, easily integrate with commercially available Zigbee-controllable lamps and luminaires for a low-cost networked lighting control retrofit.

Development of PermaMote

The research team developed a low-cost sensing platform with distributed intelligence and communications. The “PermaMote” is a self-powered sensor platform for lighting applications, with multiple sensor types (light level, light color, motion, temperature, humidity, pressure, acceleration). The energy harvesting capability of the PermaMote permits it to operate for an indefinite period in areas with regular access to light, avoiding the expense of battery replacement. The small size and weight of the PermaMote, shown in Figure 1, allow it to adhere to almost any surface in the work environment, which permits more accurate measurement and control of illuminance on the work plane. The high level of integration and standardization allows production of PermaMotes at a projected high-volume cost that is much lower than current commercially-available self-powered sensors.

Figure 1: PermaMote design



Most existing commercial lighting control systems have sensors that are wired into existing luminaires or connected to the building's electrical backbone. In order to capture maximum energy savings from lighting control, highly granular control over primary and task lighting is required as well as the ability to measure a number of important variables like occupancy. These two critical gaps in technology were addressed by developing low-cost, wireless and energy harvesting sensors that can connect to existing lighting control systems using an open API. Having these would allow building owners and managers to extend the reach and capability of already-installed lighting control systems in a simple and cost effective manner.

The Permamotes are capable of implementing most major lighting control strategies such as occupancy-based control, daylight integrated control and personal as well as institutional tuning (institutional tuning refers to dimming lighting fixtures below their original nameplate ratings to achieve appropriate light levels at the task plane). The sensors will be calibrated for two particular use cases that are most common in commercial buildings: 1) perimeter private office with single occupancy, and 2) an open plan office with multiple occupants. Based on the use cases and a market survey of existing specifications of sensors being used in commercial lighting control systems, specific functional specifications for the sensors were decided upon.

In addition, cost targets for each sensor module were developed based on prevailing costs and predicted reduction in the near future based on economies of scale. Accordingly, it is expected that the sensor module designed as per the specifications will cost approximately $15 - $20 /unit at high volume of ten thousand or more units. The system lifetime is assumed to be between 5 and 10 years and will be determined by the final design and implementation. The batteries present in the sensors, which are rechargeable and are charged by the on-board photovoltaic panel, are likely to be the most critical factor in determining lifetime.

Development of RAD Controller

This project also focused on refining and field-testing a novel daylight harvesting system. This device is a lighting controller called the RAD controller (for “Readings-At-Desk”), which is designed for placement within office users’ workstations. The RAD controller: 1) measures the amount of light present in the workstation, 2) allows the user to define how much light they desire to have in the workstation, and 3) wirelessly communicates to wirelessly-controllable overhead lighting systems that illuminate the workstation such that measured light levels match requested light levels where possible. The user interacts with the RAD controller by adjusting a slider that corresponds to the light level they desire and the system automatically adjusts to maintain this light level (e.g., as daylight levels increase or decrease).

Typically lighting control systems utilize daylight sensors located at the ceiling-plane. The advantage of using sensors that are co-located at the occupants’ work-plane rather than at the ceiling-plane is clear. It is simply more accurate to measure work-plane illuminance directly than to try to estimate it from afar (i.e., 5 – 8 feet above, or more, in the ceiling-plane depending upon the fixture or sensor location). Lighting conditions vary greatly within a space and throughout the day in non-linear ways that are extremely difficult to accurately model. Consequently, control systems that adjust lights based on ceiling-located sensors often over-dim or under-dim. In fact, many systems will over-dim for parts of the day (depriving users of needed lighting service) and under-dim at other times (missing opportunities for energy-savings).

This project extends the RAD controller research and development that was originally funded by the CEC’s Energy Innovations Small Grant (EISG) program. The EISG project explored the feasibility of a local-sensing approach to daylight harvesting and resulted in four prototype systems. In these prototypes, the RAD controller was housed in an LED task light – a convenient location as the task lamp has power that can be used by the RAD controller, is likely to be placed at a location where lighting it needed, and allows a light sensor to be placed on the top of the task light head - a location where it is unlikely to be shaded or obstructed. These prototypes required a second piece of hardware to be installed in the ceiling in order to control the overhead lights. The ceiling device would receive a Wi-Fi signal from the RAD controller (e.g., turn light up one step) and convert this to a 0-10V-control signal for controlling 0-10V ballasts or drivers.

Refinement of RAD Controller

Starting with an initial field test, researchers then turned their attention to developing the next generation of RAD controller. Refinements of the new RAD controller were driven by the following three factors:

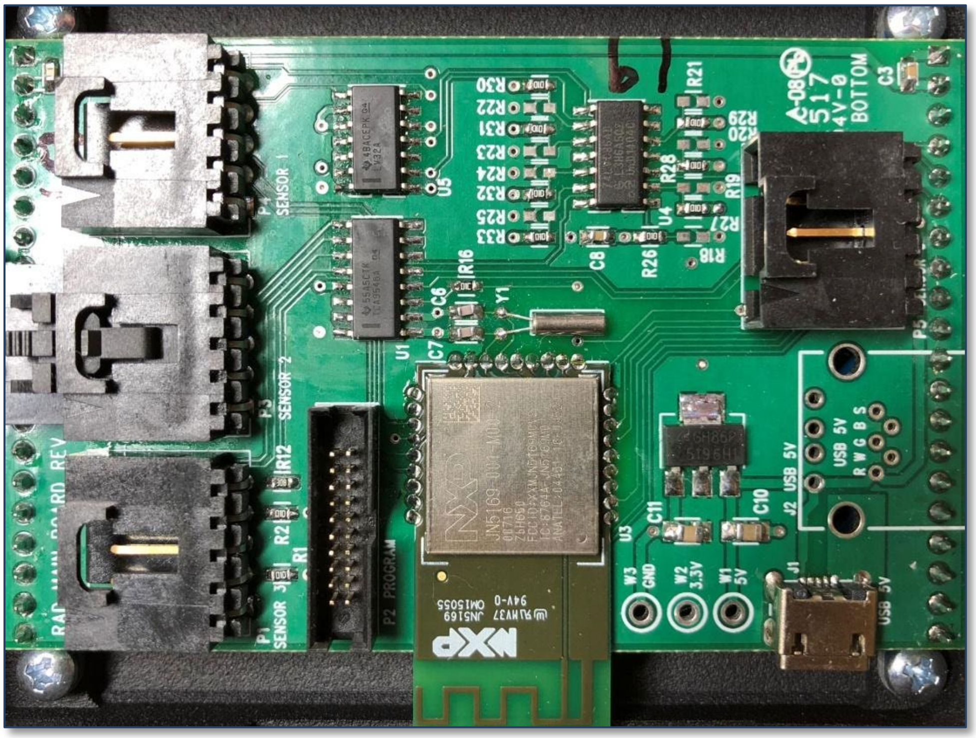
1. *Results from initial field test*: While the results from the initial field test were largely positive, there were a number of performance and user interface items that were identified as areas for potential improvement. These included developing a more robust networking architecture, simplifying systems installation associated with the control of the overhead lamps, and developing a more intuitive user interface.
2. *Changes in the Marketplace*: Several years had passed between the initial development of the original RAD controller and the initiation of this new development phase. In the meantime, the wireless lighting controls landscape had been evolving rapidly, and in ways that presented new opportunities for the RAD controller. Specifically, the emergence of open wireless lighting control architectures, such as Zigbee, allowed researchers to focus entirely on the workstation-based controller that then could wirelessly connect and control any lamps or luminaires that were based on these open architectures. This approach had the advantages of simplifying system design and removing the significant installation and cost barrier associated with the prior system's ceiling controller.
3. Focus on Commercialization: Initial prototypes were constructed primarily as a "proof-of-concept" with little attention or intent on placed on commercialization, resulting in systems that would be impractical and expensive to commercially produce. In developing the new generation RAD controller development, researchers developed "pre-commercial" prototypes where cost and scalability were important design considerations and constraints.

The development of the new RAD controller culminated in the design and production of a custom circuit board (see Figure 2) and associated software that utilized a microcontroller with an integrated Zigbee radio. Key technical specifications of the RAD controller include:

- NXP JN5169 low-power Microcontroller with integrated Zigbee radio
- 2.8" color touchscreen display
- Tri-stimulus color sensor
- 3 additional I2C sensor sockets for additional measurement needs (e.g., temperature, VOC, other light spectra, etc.)
- 4 additional digital inputs (including occupancy sensor measurements)

- USB powered

Figure 2: New generation RAD controller circuit board



RAD controllers were produced and ultimately field-tested in two different form factors. Figure 3 below shows the first embodiment in which the RAD controller is housed in a custom 3D printed case approximately 3” x 2” x 1” and is designed to either sit on the user’s desk near their primary work area or mount to their monitor. In the photo on the left, the light sensor is seen on the top of the RAD controller while the photo on the right shows touchscreen that displays the current light level and allows the user to increase/decrease their requested light level by dragging a virtual slider.

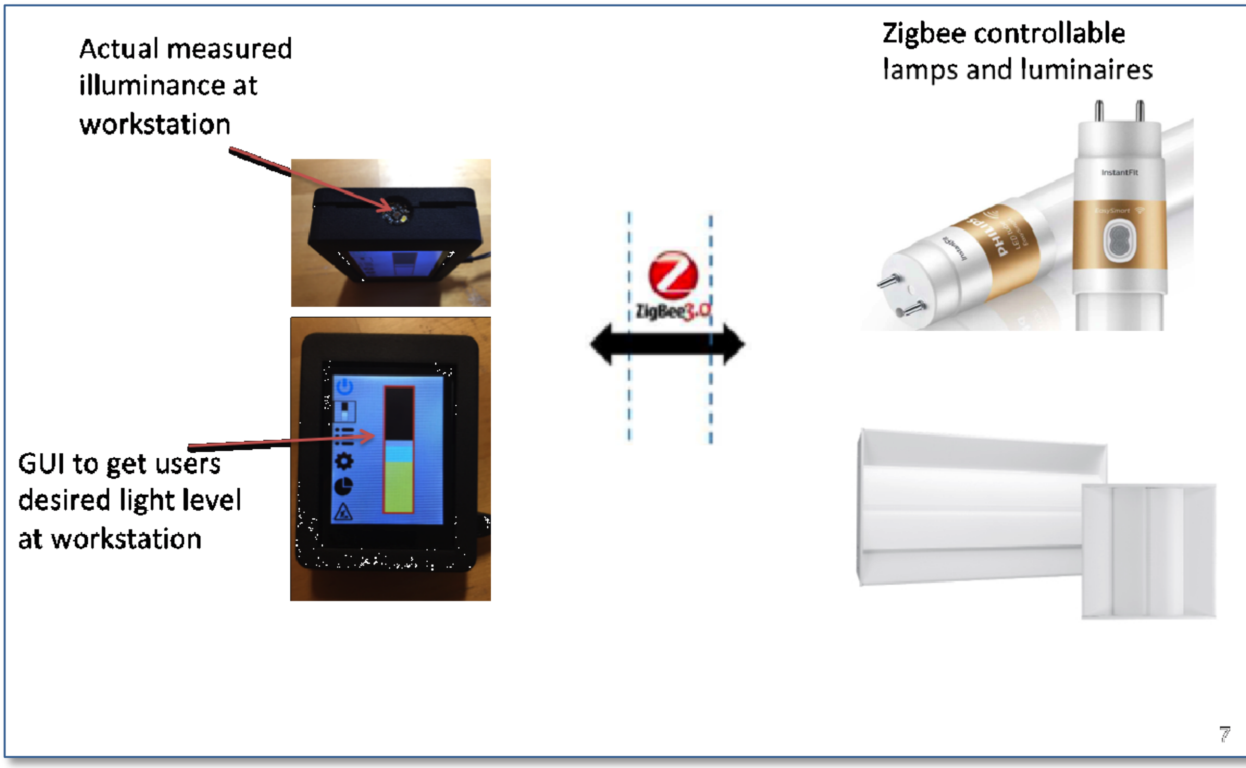
Figure 3: Desktop versions of RAD controller

The photos in Figure 4 show another embodiment in which the RAD controller is integrated into a task lamp. This embodiment places the light sensor remotely to the top of the task lamp where it is unlikely to be shaded and is closer to the user's eye level.

Figure 4: Task light integrated version of RAD controller

Figure 5 presents a schematic of the RAD controller operation from either of these embodiments. As shown, the RAD controller receives input information on actual light levels (as measured from the sensor) and requested light levels (from user interface) as inputs to its control algorithm. These are used to create output Zigbee control commands to the connected Zigbee lamps and/or luminaires.

Figure 5: Control schematic for RAD controller



These systems were built, tested, and refined over a several-month period. Ultimately 20 RAD controllers (10 desktop, 10 task lamp integrated) were produced for field-testing. The researchers note that several industrial partners provided significant in-kind contributions during this project. These include a close collaboration with LightCorp, which provided the tasks lamps that were utilized and provided significant engineering support in modifying these task lamps to accept the RAD controller and associated sensors. The researchers also acknowledge the significant assistant provided by Philips Lighting. Philips provided pre-production prototypes of their Zigbee controllable EasySmart TLEDs during the project's development phase and provided valuable engineering support related to Zigbee software development.

Lab Testing of the Networked Lighting Systems

Testing of the PermaMote Sensors

Functional testing

The occupancy and light sensors integrated into the PermaMote were first tested in the lab to verify performance. Further details on functional testing of the sensors are provided in Appendix II.

For occupancy, a protocol was defined for lab testing carried out to characterize the PermaMote sensor's ability to detect motion, per the performance targets from the sensor specification. The PermaMote's performance was characterized according to principles laid out in the NEMA WD 7-2011 (R2016) Occupancy Motion Sensors Standard.

The PermaMote occupancy sensor was found to be responsive to motion, within expected sensitivity based on manufacturer specification on field of view for the sensor at the mounting height tested (9' 4"). For major motions (subject movement between 3' by 3' cells under sensor), the detection area was around 21' x 18', close to our sensor specification of 20'x 20' (albeit that specification was for 8' mounting height). For minor motions (smaller motions within the 3' by 3' cell) the field of view was found to be around a 6' radius from sensor center, better than the sensor specification requirement of 5'x 5' detection area.

A test protocol was also developed for the light sensor. The objectives of light sensor testing were to characterize the Mote sensor's ability to measure visible light intensity (in lux) as well as color parameters (red, green, blue, or RGB counts) that can be converted to color temperature (in degrees Kelvin). The performance of two PermaMotes was evaluated under several light sources and different conditions. Performance was characterized against reference lighting intensity and color temperature measurements from a lab grade spectral illuminance meter, with a second photosensor serving as a check against the reference meter.

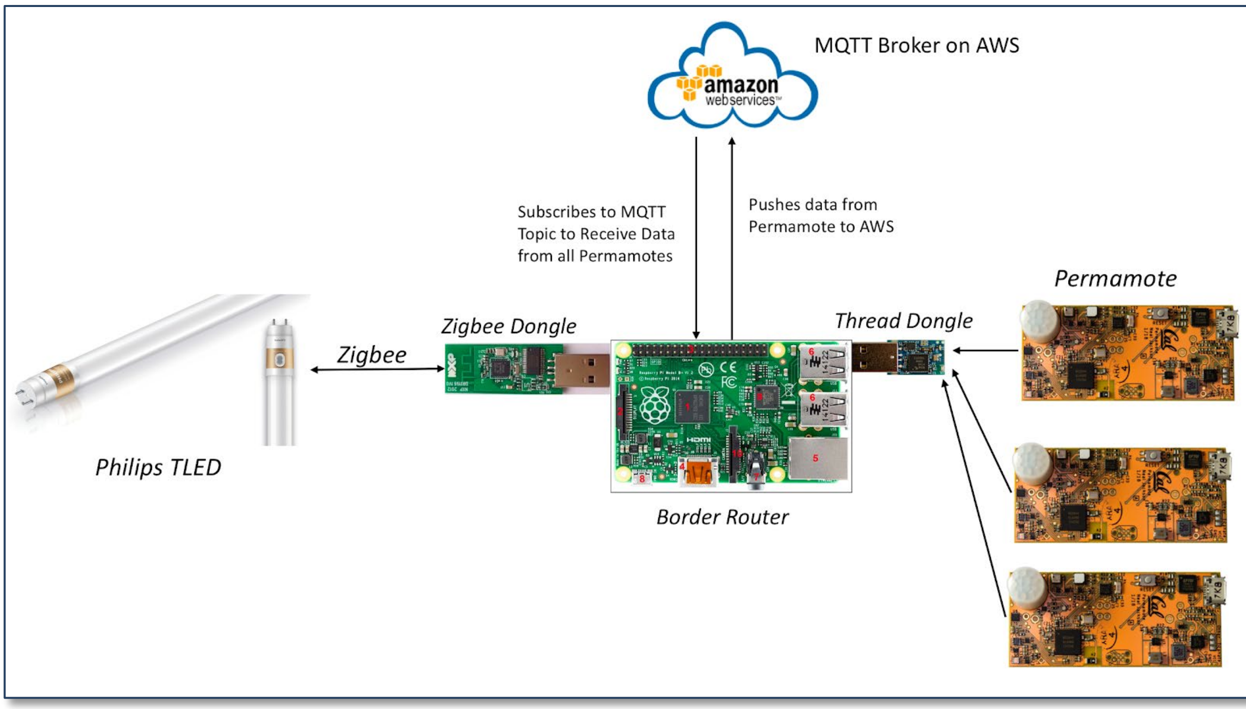
The PermaMote sensors were found to be proportionally responsive to light intensity, in agreement with the reference illuminance measurements. Dynamic range was found to be from zero to over 4000 lux, well over the 2500 lux specification. However, the sensitivity of the sensors appears to be low, and may require some adjustment to sensitivity settings or post processing. For light levels below 1000 lux as measured by the reference sensor, the sensors' illuminance measurements were found to be about 20% lower than actual illuminance as measured by the reference sensor. At lower light levels the sensors more closely matched reference measurements and at higher light levels the Mote sensors were found to deviate further.

The research team measured color temperature (CCT, Kelvin) and spectral data by the reference sensor as well. The PermaMote sensors measured RGB (analog), which could be post-processed to CCT for comparison with measured CCT results.

Integrated system testing

With the PermaMote sensor package successfully characterized through sensor testing (post design), it was then important to test PermaMote sensors functionality when integrated into a lighting system architecture. Prior to deploying sensors and controls in occupied space, basic functionality of the integrated system (PermaMote communicating with a lighting controller and light source) had to be proven. Several tests were carried out to ensure stable and proper operation. The PermaMotes were paired with wirelessly controlled LED replacement lamps (TLEDs) for fluorescent fixtures. The system architecture that was implemented for the functionality and performance tests is shown in Figure 6.

Figure 6: Zigbee TLED controlled by intelligent task light



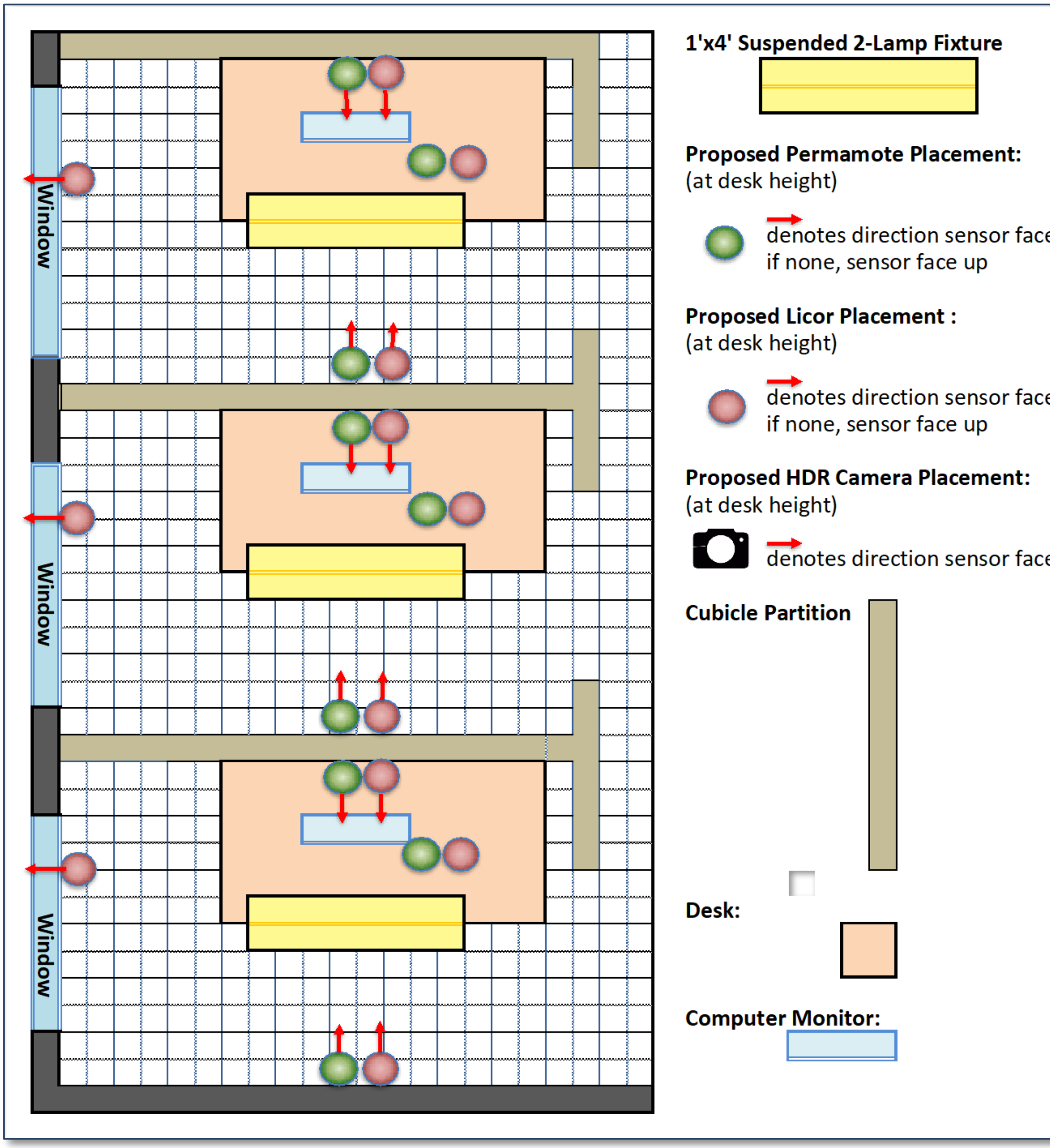
Once the functionality of the occupancy control and daylighting control features were proven, the PermaMotes were ready for performance testing in an occupied environment over time, to measure and verify operation and energy savings in a more “real world” implementation. This test was designed to characterize performance of the wireless control, self-powered features, and daylighting and occupancy sensing performance. A networked lighting system of that architecture was set up for installation in the FLEXLAB® Lighting and Plug Load occupied testbed, which is a cubicle-style open office environment with a typical pattern of occupancy during workdays. The layout for this test is shown in Figure 7.

This project tested the daylighting and occupancy functions and the lighting and energy performance of the wireless self-powered sensors for control of overhead lighting via wirelessly controlled LED replacement tubes. The FLEXLAB® testing consisted of three occupied offices with south-facing windows; a reference office with basic scheduled lighting control, and two test offices where the PermaMote lighting controls were implemented. All offices had suspended direct/indirect two-lamp T8 fluorescent fixtures.

PermaMotes were placed at identical locations in each office (on the desk surface, as well as on cubicle walls and the ceiling). Several PermaMotes were placed in each office to capture spatial variations in illuminance measurements. In the reference office, the devices only measured and reported light and occupancy. In the test offices, the PermaMote occupancy sensors were used for automated on/off control and the photosensors were used to measure light levels and control the electric lighting to dim or brighten to meet setpoint.

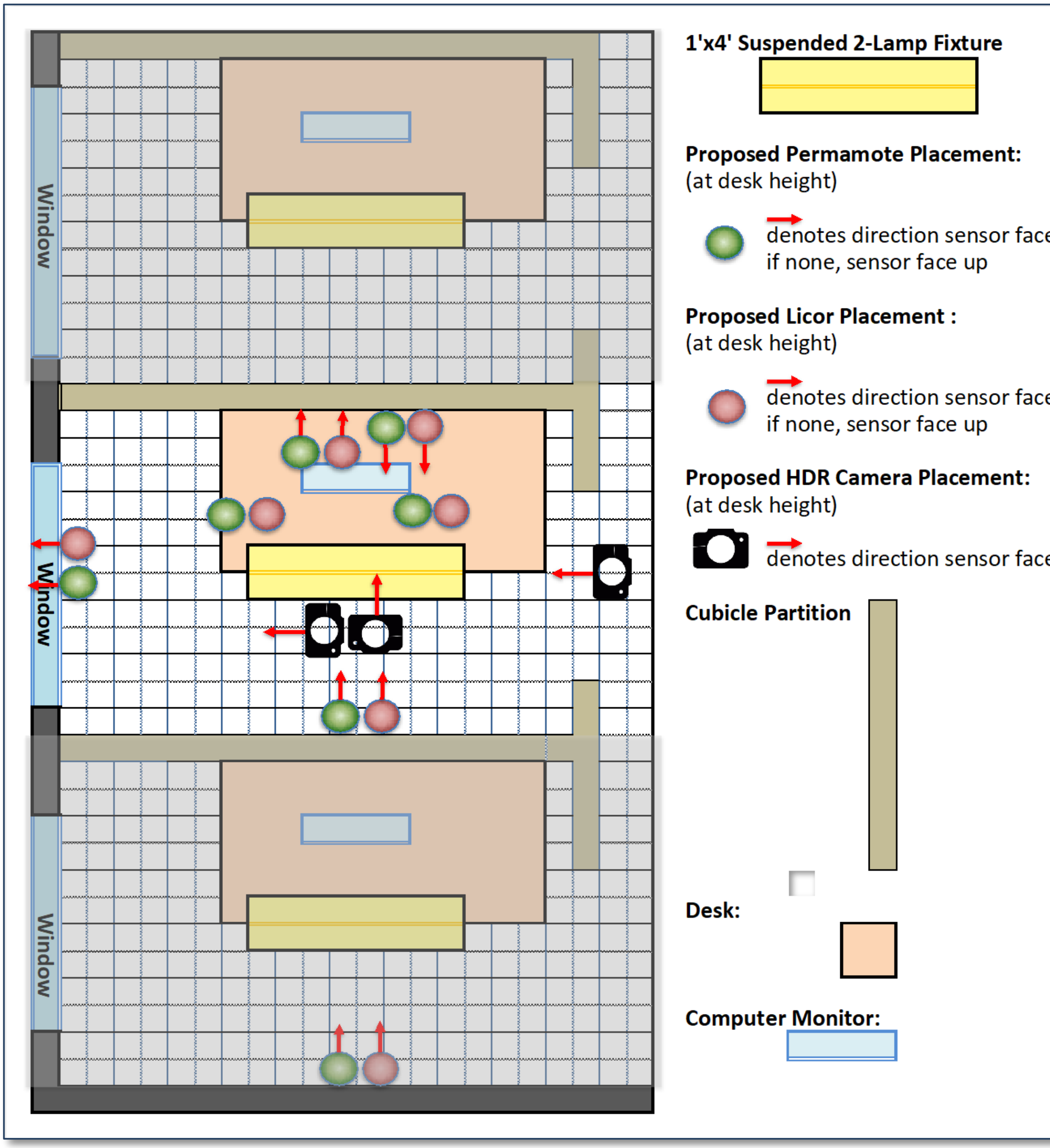
The devices used in the test setup were PermaMote sensors, wirelessly controlled TLEDs and compatible suspended direct-indirect fixtures, and sensors and loggers to obtain reference illuminance levels for comparison. A Wattstopper Digital Lighting Management (DLM) system was used to control a baseline lighting system (same fixture and TLEDs but programmed only for scheduled daily on/off operation).

Figure 7: Sensor layout for performance test in FLEXLAB



Glare parameters were measured in the test space through time (weekend test only to avoid disturbing occupants with HDR cameras) to compare with data from the wireless sensors in order to establish relationships between spatial illuminance variations and measured glare data, using daylight glare probability as measured by HDR cameras and comparing HDR data to illuminance data. The setup for this test is shown in Figure 8.

Figure 8: Sensor layout for glare testing in FLEXLAB

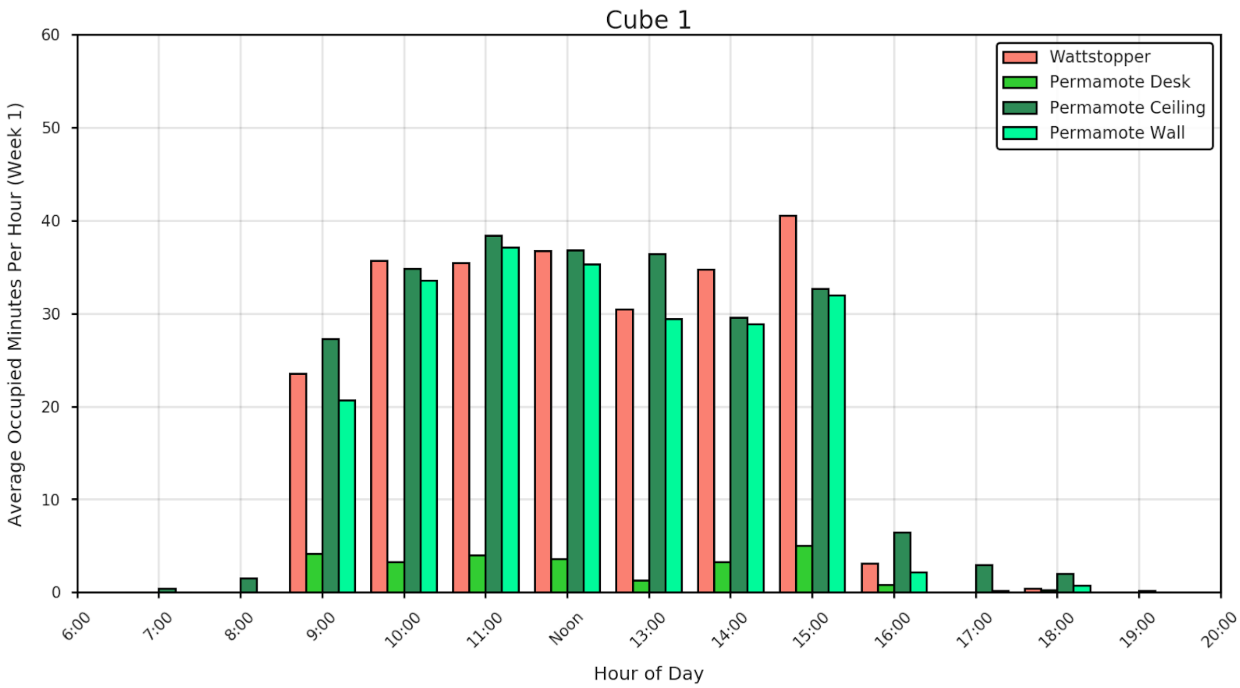


Overall the PermaMotes performed as intended during the integrated testing of daylighting and occupancy control. They were successfully integrated into the lighting system via the architecture previously described and successfully controlled the lights based on sensor inputs and controls programming. The energy-harvesting feature of the motes also worked well; they operated successfully for the full 2-week period.

Occupancy

Since PermaMotes are wireless and self-powered they can be placed anywhere in the office that is practical. In this test, the desk-based PermaMote that was used for daylight control was also used for occupancy control. It was found that the PermaMote on the wall and on the ceiling in cube 1 and 2 had more reliable occupancy readings (closer to the reference narrow-field ceiling-mounted Wattstopper occupancy sensor) than the desk-based sensor, especially in cube 1 as shown in Figure 9. A future implementation of the system could rely on the desk sensor for light level control and a sensor elsewhere for occupancy control.

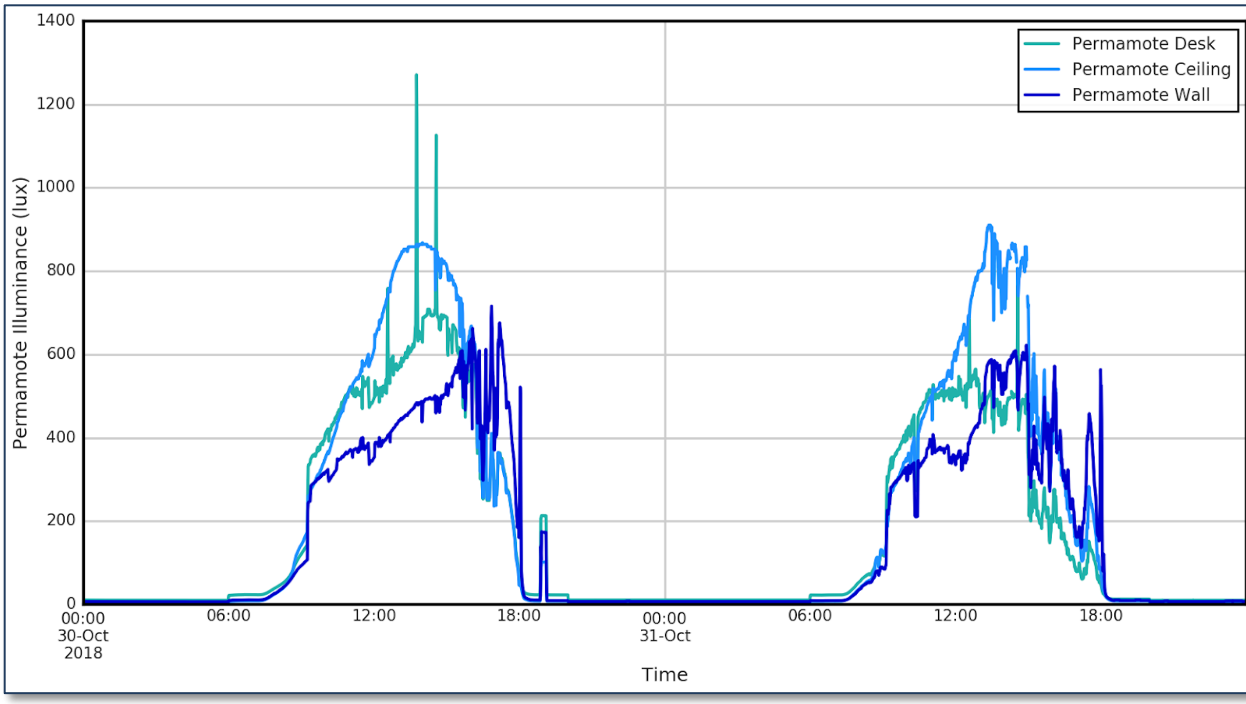
Figure 9: Occupancy test results from PermaMotes.



Light Levels

During the experiment, light levels were measured by PermaMotes placed at each cube's desk as well as on the ceiling over the desk facing down and on the nearest wall behind the desk, facing the desk. An example of the light levels measured through time at these various locations is shown in Figure 10.

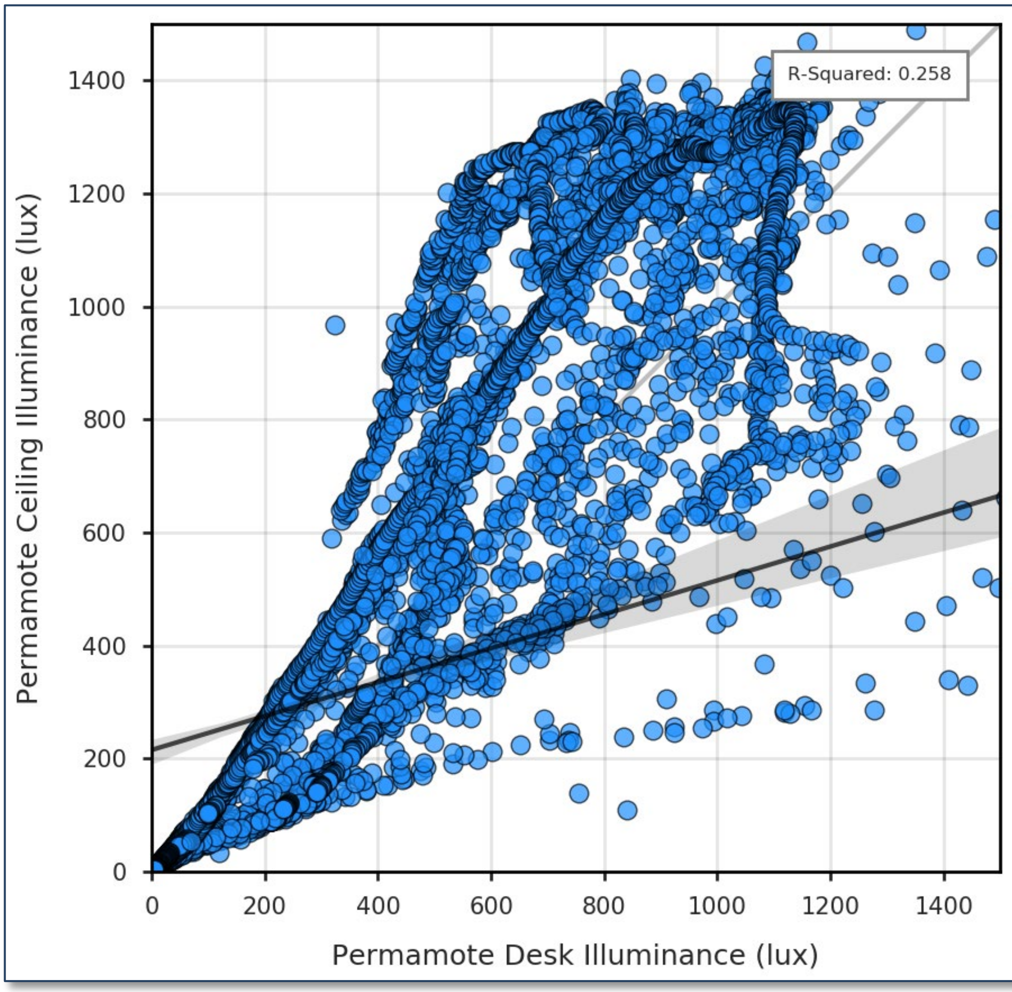
Figure 10: Light testing of PermaMotes in FLEXLAB®.



The premise of most closed-loop daylight control systems is to use a ceiling mounted photosensor as the control point that is used to determine how much electric light to provide a space, even though the desk is the primary target of illuminance. The light at the ceiling will not be the same as at the desk so the ceiling-based sensor approach assumes a consistent relationship between the illuminance at the one location and the other (i.e. a consistent ceiling to task ratio). Typically, during set up and commissioning the lighting system would be designed and possibly tuned to meet the desk illuminance target (in the absence of daylight) and whatever light level is measured by the ceiling sensor during commissioning as the daylighting setpoint that the system tries to maintain.

However, this premise will only maintain the intended desk illuminance target accurately if the relationship between the desk and ceiling illuminance is roughly constant and proportional. The PermaMote system avoids any uncertainty as to the relationship between illuminance in some other location in the office and the illuminance at the desk because the sensor can be placed directly on the desk. Consider the ceiling to desk illuminance relationships in Cube 1 illustrated below in Figure 11. For Cube 1 a ceiling mounted light sensor would have been a poor control point for lighting the desk, as the two were not well correlated.

Figure 11: Light level correlation between reading at desk and reading at ceiling

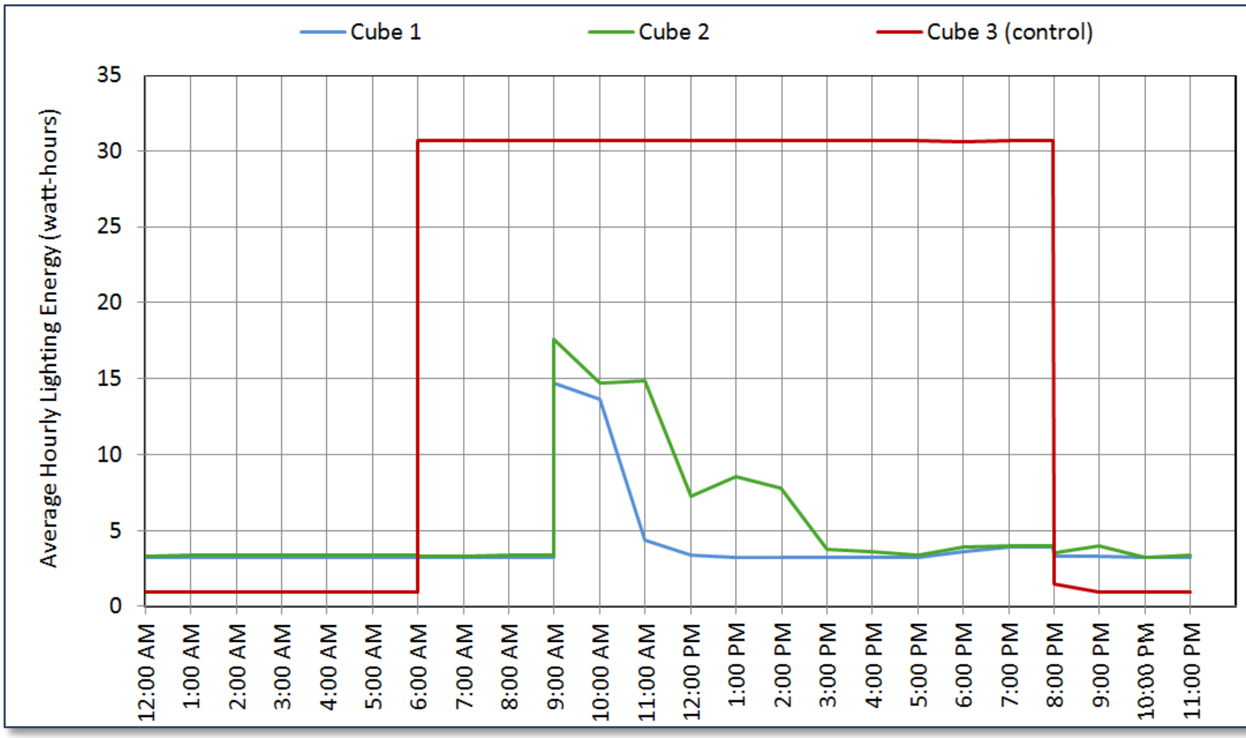


Lighting energy savings

The reference office, cube 3, was controlled by a networked room controller with on/off relay scheduled to operate the fixture from 6AM to 8PM. The networked controller required around 1W of standby power to operate. The test cubes, 1 and 2, relied on the wireless controls in the on-board LED lamps to operate. The LED lamps also require some standby load in order to maintain wireless connectivity for controls purposes; measured at around 3W per fixture for the two lamps.

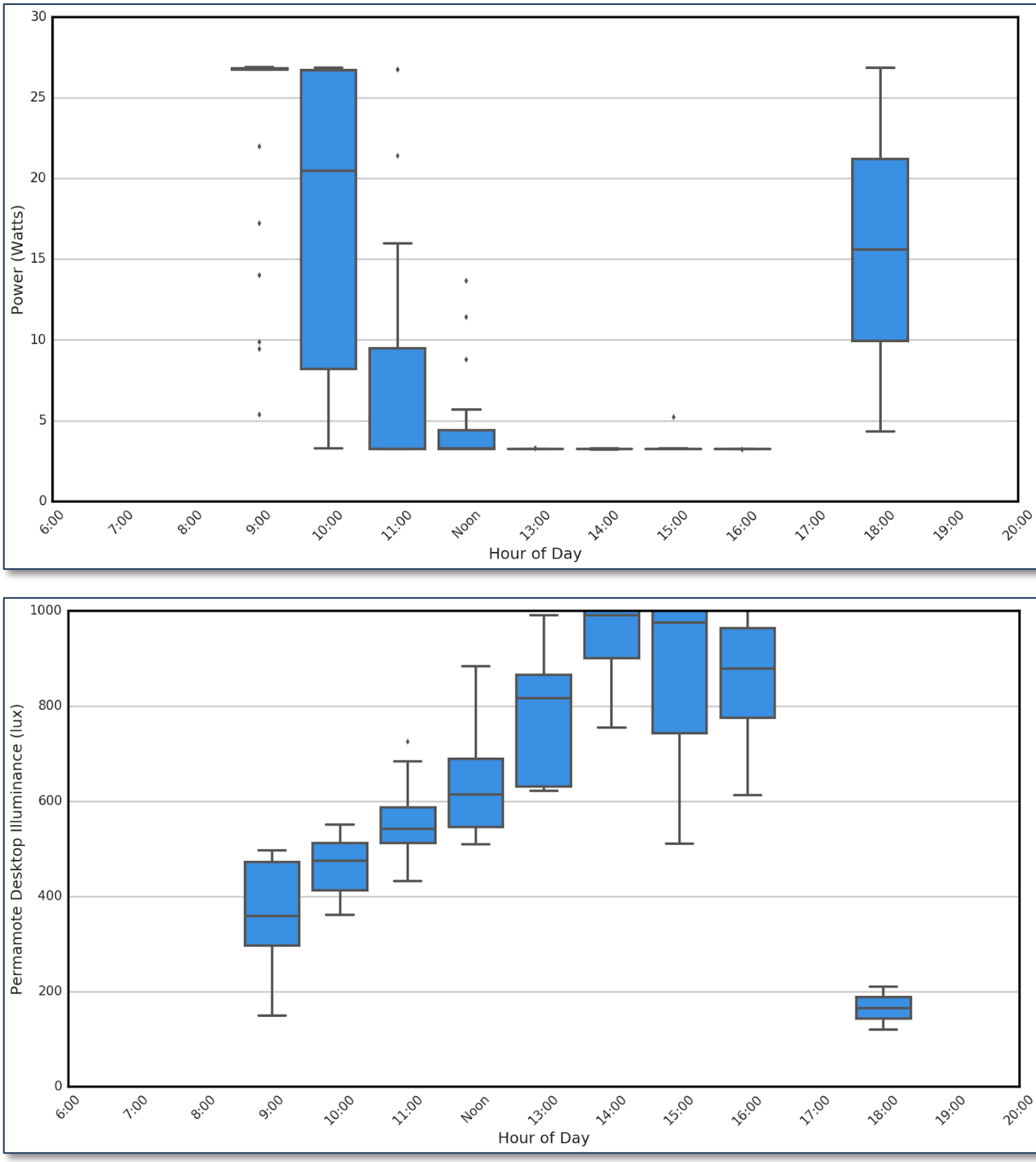
With the occupancy control and daylight dimming features, cubes 1 and 2 saved an average of around 73% energy for the week-long test period; 0.10 to 0.13 kWh/day compared to 0.44 kWh/day as shown in Figure 12. This result is impressive but it should be noted that for cubicle 1 and to a lesser extent cubicle 2, the occupancy sensor of the desk-mounted PermaMote under-estimated occupancy so the LED lights were sometimes off when an occupant was present and they should have been on (even if dimmed due to daylighting). Therefore, the energy savings are greater than what would be expected if a different occupancy sensor location, such as the wall or ceiling were used as the control point.

Figure 12: Comparison of average hourly energy consumption across test cubicles



The box plots in Figure 13 below portray the distribution of lighting power levels and desktop illuminance levels (as measured by the PermaMote) for the time periods during which the test offices were occupied according to the PermaMote sensor. These plots illustrate the median hourly (e.g., 1:00PM to 1:59PM) power and light levels in the offices, when occupied. The general trend in the plots is that the fixtures are on at or near full power in the morning when the occupant arrives but daylight levels are low, and the fixtures are dimmed or turned off later in the day when the light level is at or above the programmed setpoint (the test cubicles faced toward the West, so received greater daylight illumination in the afternoon).

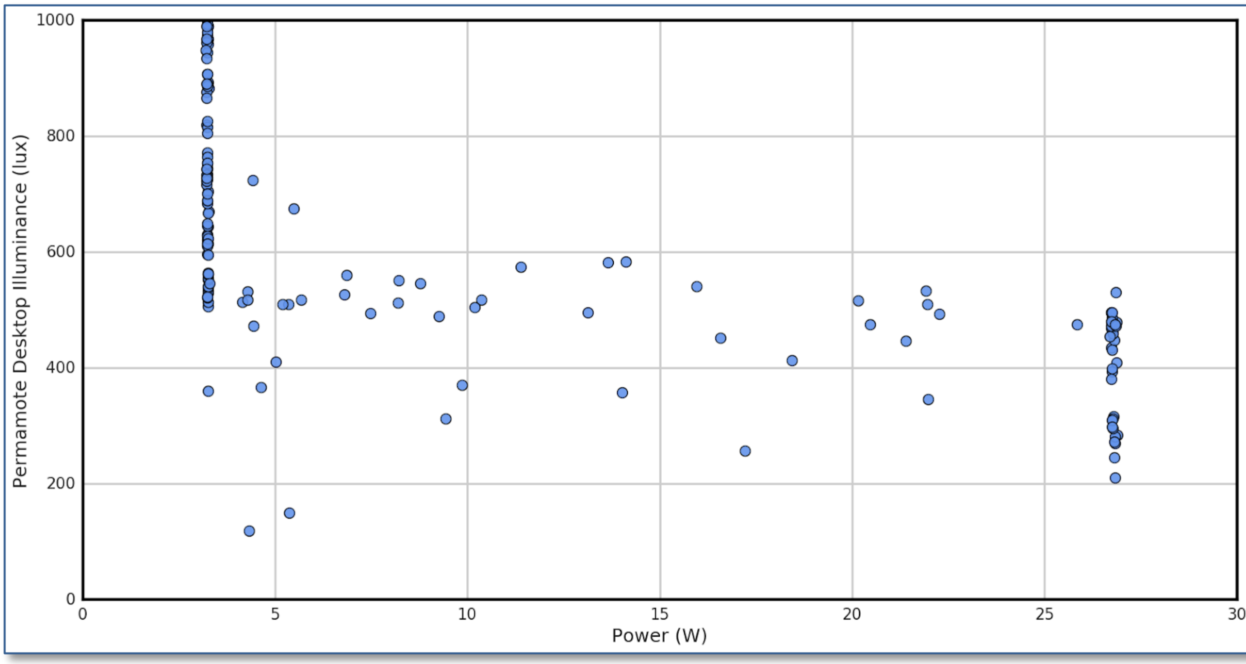
Figure 13: Cube 1 hourly distribution of fixture power and PermaMote-measured desk illuminance (occupied periods)



Another way of examining the daylight dimming behavior of the fixtures is to see whether the system is adequately maintaining the lighting setpoint, as shown in a scatterplot of illuminance and fixture power levels for all occupied instances in the dataset (Figure 14).

The fixtures are at lowest power (off, but with some standby load) for most of the illuminance data points above the 500 lux target. These data points are essentially measurements of only daylight. The trends then show a range of fixture power levels for which the desk illuminance is around 500 lux; indicating a mix of daylighting and electric power that sum to the lighting target. Finally, at full fixture power there is a range of illuminance values from near the set-point to well below it. These are essentially measurements of diminishing and zero daylight, and full electric light, which alone is insufficient to meet the 500 lux target.

Figure 14: Lighting power for varying illuminance levels at desktop with set-point of 500 lux



Preliminary Glare Analysis

Glare measurements were taken throughout a test office over the course of two days (November 10 – 11, 2018) at two locations; the occupant's desk chair at seated height and facing the window (worst case condition) and the cubicle entryway at standing height also facing the window wall. Along with glare, which was characterized with the DGP metric and measured using the HDR cameras and processors, illuminance was measured for locations throughout the office with the PermaMote sensors and with Licor illuminance sensors. For the two-day dataset of illuminance and glare, simple correlations were computed between each measurement point based on least squares regression in order to evaluate which illuminance measurement locations had the strongest correlation to the glare values. Subsequently a simple machine learning exploration of the data was done using a single two-layer neural net model to predict glare at the desk location from all of the illuminance data points. The model was able to accurately predict DGP with an average accuracy of 91%, and an average error of 0.024. As this simple model was only trained with the two days and for one specific glare location at the desk, the results are overfit but help prove the concept that glare can be predicted from illuminance measurements such as those provided by PermaMotes deployed throughout an office environment. More data collection and computation will be necessary to further explore the possibility of using wireless illuminance sensors in an office to predict glare for the occupant, which the research team intends to pursue in future work.

Figure 15 below shows a correlation table for all of the illuminance measurement points (licor values) and the glare measurement points (DGP cameras). Red indicates values with an R^2 closer to 1 and blue indicates an R^2 closer to zero. Figure 16 shows the glare prediction made by the machine learning neural net model using the illuminance values as inputs.

Figure 15: Correlation table for glare analysis

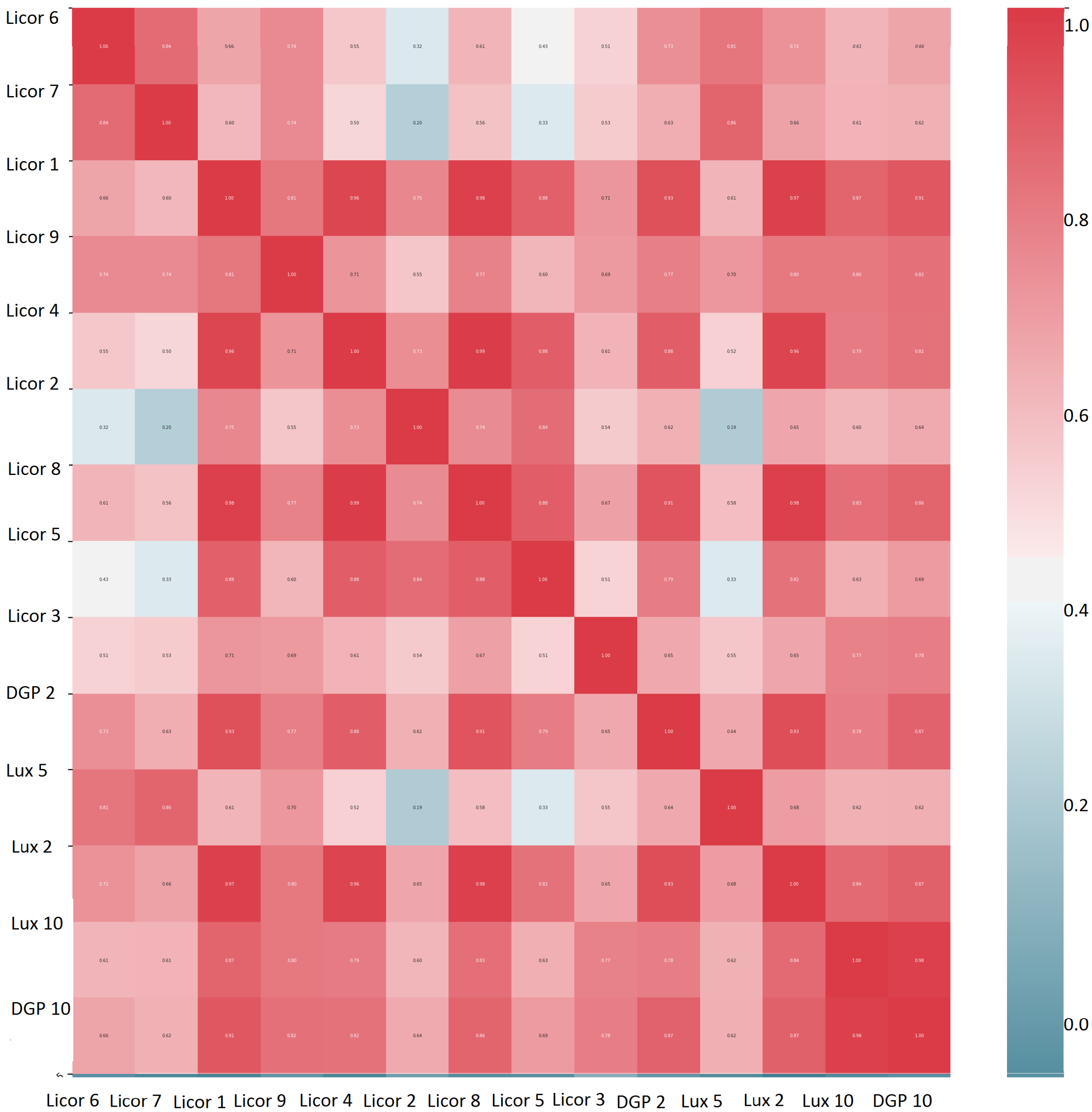
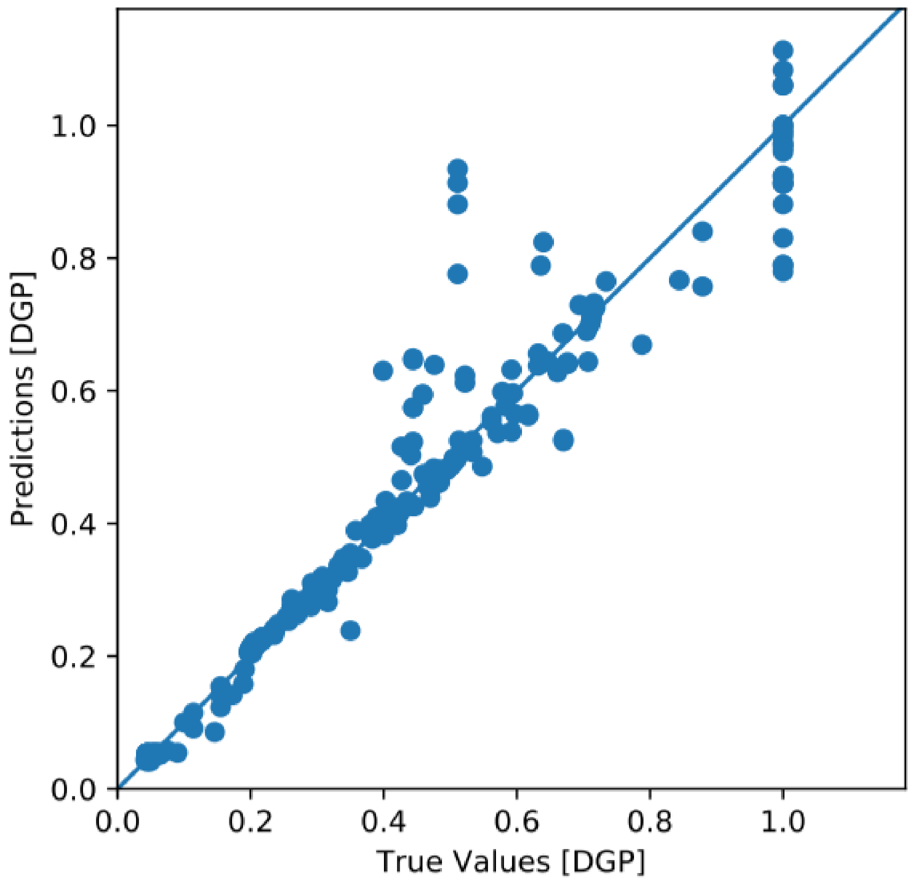


Figure 16: Glare prediction using illuminance measurements and machine learning



Testing of the RAD Controller

Initial Field Test:

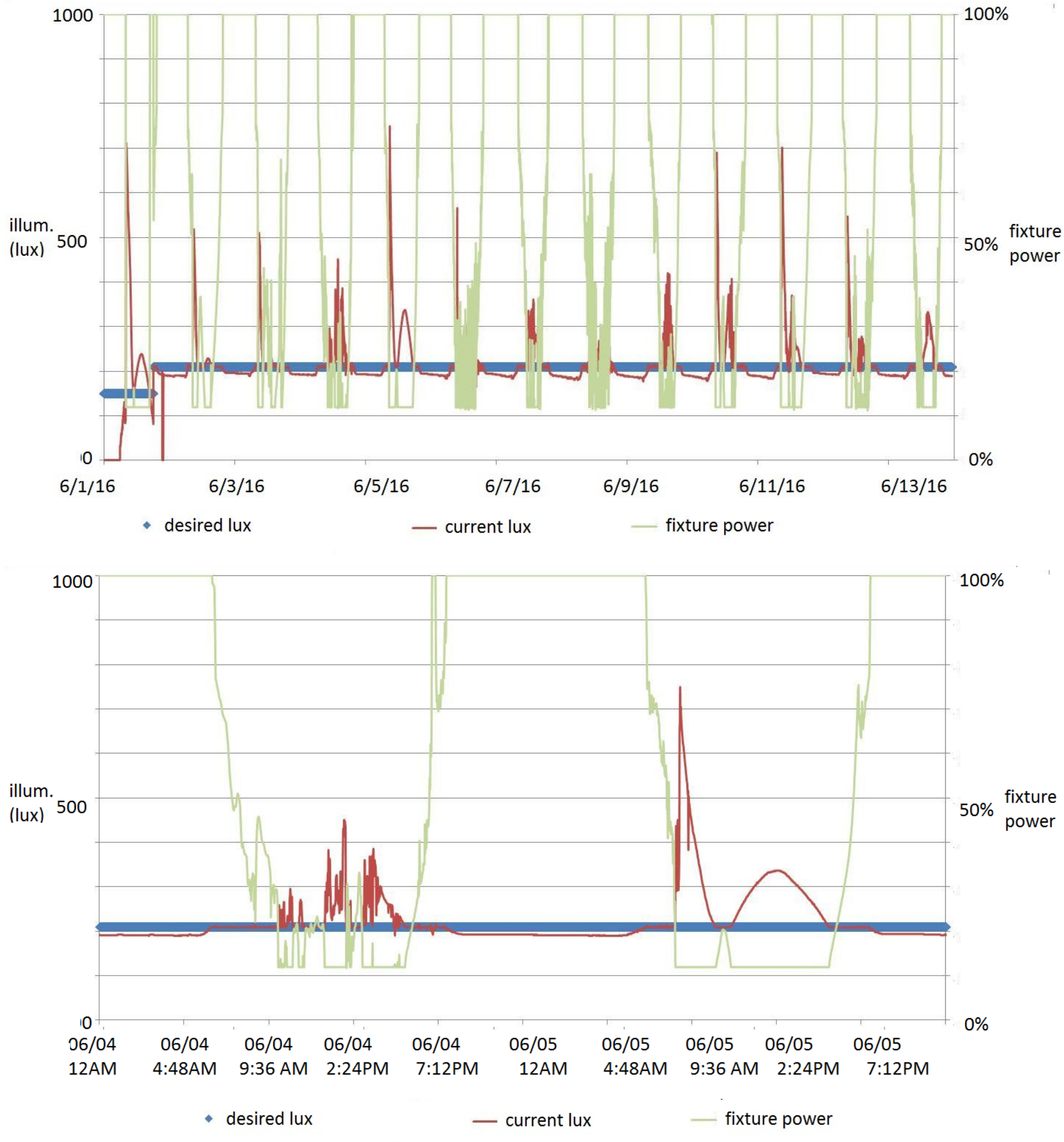
The RAD controllers used in the initial field test were produced during a previous EISG project and were housed in LED task lamps. The initial field test involved testing three of these systems for six weeks in LBNL's FLEXLAB® Lighting and Plug Load occupied test bed. Figure 17 shows one of these prototypes installed on the desk of one of the participants of the initial field test. These initial prototypes had an LCD display that provided a readout of how much light was falling on the task lamp (from daylight and overhead lighting) and how much light the user was currently requesting. It also included push buttons that allowed users to increase or decrease the requested light levels. The LED task light itself was controlled separately and its light output was not affected by the RAD controller or changes in daylight levels.

Figure 17: Initial RAD controller prototype in FLEXLAB

Figure 18 shows an example of the primary data recorded and analyzed during this field test. The top graph shows a two-week period for one RAD controller while a more detailed view of two days during this period is shown on the bottom graph. On these graphs, the requested light level (blue line) and measured light level (red line) are displayed, in values of lux, as indicated on the primary y-axis. The relative luminaire power is shown in green in values displayed on the secondary y-axis (e.g., luminaire at full power = 100%; luminaire fully dimmed = 12%; luminaires off = 0%).

During the test period, all prototypes performed as expected, increasing the luminaire light output (and associated power) when daylight was limited and decreasing light output when daylight was abundant. This pattern is seen in the bottom plot in Figure 18, with the daily pattern of the luminaire dimming to minimum power as the sun comes up and ramping back up to full power at night. The bottom plot shows a cloudy day followed by a sunny day. The cloudy day has variable daylight, which requires more active changes in electric light to maintain a desired overall light level, while the sunny day has smoother changes in daylight and the required luminaire's response.

Figure 18: Two weeks of data from one RAD controller (top) and close up view of two days (bottom).



Other findings from Field Test #1 included the following:

- One of the RAD controllers was placed in a location with very high daylight levels. The overhead lights in this cubicle were found to be at a minimum level nearly 100% of the time because the user requested level was nearly always less than the daylight level. A second location had low daylight levels and the user had a preference for very high light levels. Thus, the user requested the maximum light level setting and the overhead lights in this cubicle we found to be at a maximum level nearly 100% of the time. The third cubicle was "just right" and with user requested levels in the same range as daylight levels. Consequently, this cubicle typically saw the full range of daylight dimming during each day.

- Users typically placed the task lamps where they had desk space available rather than where they needed lighting or in an ideal location for a sensor. In several cases, the lamps were placed very near the window. This resulted in the sensor on the lamps seeing a significantly higher level of light than the user did, resulting in overly aggressive dimming of the overhead lights. After a week or so, these lamps were moved to more central locations in the office and functionality improved.
- After systems were set up and functioning well, users rarely adjusted user set points during the test period. That is, they simply left the system alone and did not increase/decrease the light levels based on time of day, weather, tasks they were doing, etc.
- In discussions with users after the field test, they indicated that the existing user interface was confusing.
- Users also indicated that a RAD system without a task lamp maybe a good idea, as it could be more easily placed at locations closer to the user.

Field Test #2

Field test #2 also took place in LBNLs FLEXLAB's Lighting and Plug Load occupied test bed, and tested the updated RAD designs shown previously in Figures 3 and 4. In this test, five desktop and four task lamp-integrated RAD controllers were installed and monitored over a six-week period. Figure 19 shows desktop and task lamp integrated RAD controllers in use during the field test. The objectives of field test #2 were the same as the initial field test: to assess the performance of the (now updated) RAD controller to perform as designed in real-world applications and to assess the user experience with the system.

Figure 19: Field test #2 included desktop (left), and task lamp-integrated (right) RAD controller versions

At the beginning of the field test, the existing fluorescent lamps in the office luminaires were re-lamped with Philips EasySmart TLEDs in each test office. Each RAD controller was then wirelessly paired to the TLEDs that were associated with the office in which the RAD controller was placed. Researchers then triggered the RAD controller's calibration routine in which the TLEDs were commanded to their brightest setting and then slowly dimmed in approximately 250 discrete steps. This allowed the RAD controllers to map the controlled TLEDs contribution to the measured illuminance at the RAD controller's location. This allows the RAD controller to, among other things, calculate daylight levels continuously during normal operation.

Shortly after the RAD controllers were installed, the systems underwent a number of on-site validation tests. One test was to simulate and vary "daylight" and confirm that the RAD controllers appropriately adjusted TLED light levels. Figure 20 shows a graph of the results for one of these validation tests. In this graph, Cmd2 is the light level value the user requests, Elec2 is the light level provided by the TLEDs, Day2 is the light level provided by daylight, and Lvl2 is the level that the TLEDs are commanded to be at. Cmd2, Elec2, and Day2 are shown in lux and are plotted against values on the primary y-axis; Lvl2 is numerical value between 1 (fully dimmed) and 253 (full light output) that represents the level the TLED is at and is plotted against the values on the secondary y-axis. The x-axis is the time of day that this test was conducted (note: test was conducted after dark to eliminated the impact of actual changes in daylight). During this test, six simulated daylight levels were evaluated over a 30-minute period, resting for five minutes each at the following levels: 1 lux, 16 lux, 53 lux, 148 lux, 190 lux, and 230 lux. The Cmd2 level was maintained at 173 lux during the entire test.

During this test (and all other similar validation tests conducted) the RAD controller adjusted lights as expected. Initially, the user was asking for more light (Cmd2 =173 lux) than the electric light could deliver (Elec2 = 103 lux) even when its lamps were at full power (Lvl2 = 253). The first two increases in daylight had no impact on the system because the combined daylight (16 lux and then 53 lux) and electric light levels (103 lux) were still less than what the user requested (173 lux). When daylight was increased to 148 lux, the TLEDs appropriately dropped to a level where they only provided 25 lux, allowing daylight plus electric light to match the user requested levels. As daylight increased beyond 173 lux, the TLEDs were reduced to their dimmest level.

Figure 20: Field Test #2 RAD controller starting verification testing graphs

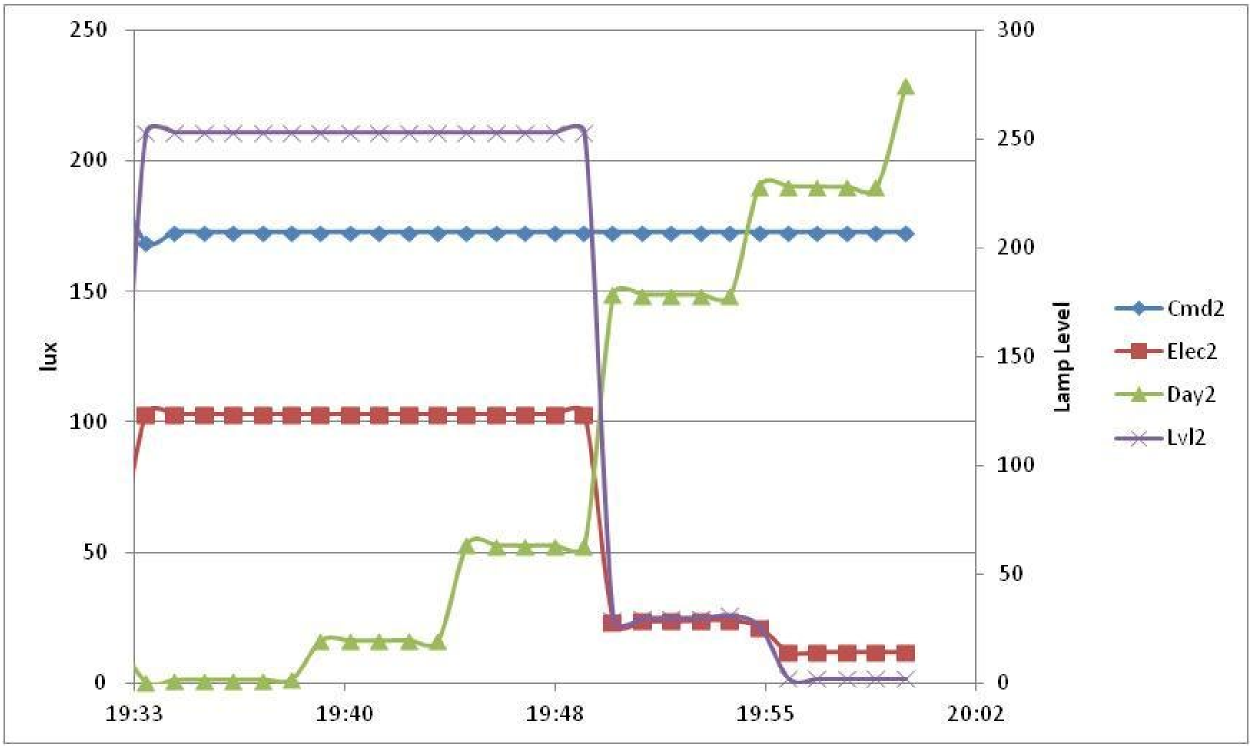
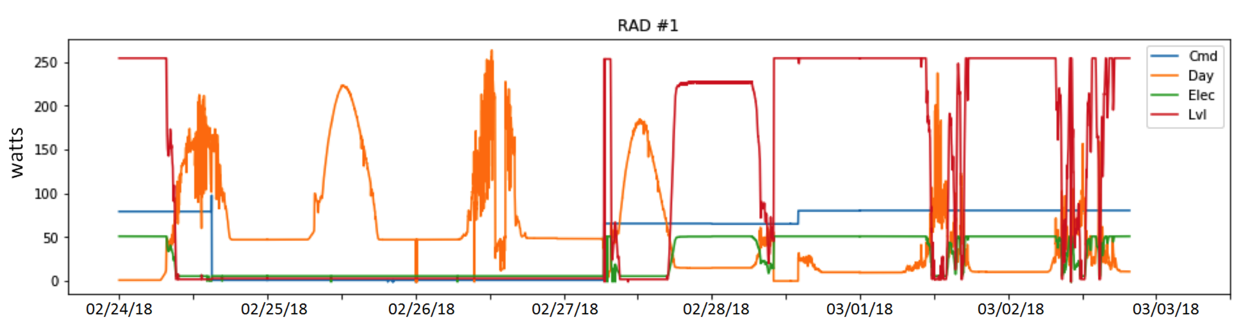


Figure 21 illustrates the performance of one of the RAD controllers during one typical week of testing. This week had a variety of sunny (smooth, continuous orange peaks) and cloudy (choppy and/or short orange peaks). The user turned their lights off over the weekend (period where only orange daylight levels are larger than zero). The user adjusted their requested level a few times (where the blue light adjusts). During all periods, the RAD controller operated as expected, turning the TLEDs up or down, based on daylight availability.

Figure 21: Performance of one RAD controller during one week of testing



Data similar to that shown in Figure 21 above were collected for all nine RADs during the entire six weeks of testing. The research findings regarding these data and the field test generally include the following:

- With some exceptions (discussed below) all nine RAD controllers performed as expected during the field test, appropriately adjusting electric light levels based on daylight conditions and/or user requires.
- In rare cases (approximately five times during testing) RAD controllers would “lock up.” During this condition, control over lights would be lost (and light levels frozen at their last commanded level) and the user input screen nonresponsive. This condition would typically be resolved by power cycling the RAD controller. Researchers believe they have identified and addressed the software bugs that contributed to these events, but internal testing continues.
- Researchers also encountered issues related to data acquisition (e.g., the collection of the light and user request data vs. time that has been shown above). During early periods of the field test, some RAD controllers would stop collecting data, requiring the researchers to reset them. These RAD controllers still controlled the TLEDs appropriately during these periods. Researchers identified and addressed the software cause of this error during the field-testing.
- Lastly, the researchers note that most of the spaces included in this study received very high levels of daylight during all working hours. Consequently, several of the participants in the study turned their lights off completely for long periods of the test. Other users kept their lights on but had user requested light levels that were low enough that the TLEDs were fully dimmed from dawn to dusk. The remaining users had higher requested light levels and/or lower daylight levels such that they had a more “active” daylight-harvesting pattern.

User feedback was largely positive. Some users noted that they still found the user interface to be confusing while other users indicated they appreciated ability of the RAD controller to allow them to adjust their light levels. Other users noted that they did not utilize their lighting much during testing because of the high levels of daylight in their offices (consist with the data discussion above).

Open Communication Standards

As part of the research to develop an open API for allowing facility managers and owners to extend the reach of wired lighting systems, the research team developed a reference data model that could be used to communicate between an existing lighting system and the low cost sensors developed in this project. With that motivation, we surveyed existing standards with the objectives of first understanding what has already been developed, and then identifying research gaps that need to be addressed before a complete data model can be described. Using this analysis, we created a list of topics necessary for a standard data model for lighting applications. Then we examined existing standards for how they address these topics for relevant information, analyze them for consistency, coverage, and quality, and then made recommendations for best practices and where further research is needed.

The core purposes of the investigation were to determine:

- Types of information to be represented for lighting applications
- Specific data elements to include
- Names for those data elements
- Data encoding (units, enumerations, etc.)

In addition to the project team's research, LBNL has also been engaging with the ANSI Committee C137, which is in the process of creating an ANSI standard for lighting control systems. As part of the committee's work, LBNL has been participating in the development of a standard data model that will be a part of the eventual standard. The current working version of this project's data model has been adapted for this project in order to avoid redundancy of work. The adapted data model is summarized in Table 1.

Table 1: Proposed data model

Data Element name	What does this data element represent?	Units	Semantic Representation	Data Type
Group ID	Identifier for a group of devices that are operated together, e.g., all lights in a room			
Scene parameters	The characteristics comprising a scene			
Illuminance target level	Illuminance level above or below which an action occurs	Lux	TargetIlluminance	Float
Device serial number	Self-explanatory		EntityModel	Text
Device firmware version number	Self-explanatory		EntityFirmware	Text
Device hardware version number	Self-explanatory		EntityHardware	Text
Device/Luminaire Location	Information as to where lights are placed such as room/cubicle/fixture description		DeviceLocation	Text
Sensor Location	Information as to where sensors are placed such as room, surface, workplane description		SensorLocation	Text
Light source CCT	Light source set CCT	Kelvin	LightCCT	Float
Sensor CCT	CCT detected by the sensor	Kelvin	SensorCCT	Float
Time of day	Self-explanatory		TimeStamp	Float or Text
Individual Sensor Occupancy	Status of individual occupancy/vacancy sensors within a room or area.		OccupancySensorState	
Room Occupancy	Current status of overall room or area occupancy, include time since last change.		RoomOccupancyState	
Individual Daylight Sensor	Status of individual daylight/photo sensors within a room or area.		DaylightSensorState	
Individual PhotoSensor Levels	Status of individual photo sensors within a room or area.		LightSensorState	
Illuminance level	Measured illuminance at a light sensor	Lux	LightSensorLevel	
LightLevel	Illuminance level in a given space	Lux	RoomLightLevel	
Luminaire Group Status	Status of a group of luminaires within a room or area, this may also be called a zone (i.e.			

Data Element name	What does this data element represent?	Units	Semantic Representation	Data Type
	light level, CCT, energy)			
Room Zone Levels	Electric Lighting status and control of each Zone			
Relay Status & Control	Status and control of individual relays (on/off)			
Device on/off state	Current (i.e., last known) state		OnOff	
LightState	Light point is on or off		LightState	
Dimmer Status and Control	Status and control of individual dimmers (light level, on/off)			
LightDim Level	0 -100% of dimming level of light. (Full on to full off)		LightDim	Float
Preset Status and Control	Status and control of presets within each space, room or area.			
Room Preset or Mode	Preset status and control			
Scene ID	Identifier for a set of characteristics that are activated together			
Room DR Mode	Status and control of DR mode			
Device energy consumption	Self-explanatory		CumulativeEnergy	Float
Power consumption	Self-explanatory		PowerLevel	Float

The project team also created a mapping between the proposed data model in Table 1 with the updated DALI standard. This was done in two steps: first was to identify the relevant parts of the DALI standard from the project's perspective and the second was to map the functions specified in the standard with those in the proposed data model.

Since the DALI standard has specific enumerations for various parameters, the LBNL mapping of the proposed data model with DALI is only limited to whether the particular parameter is represented or not. Also, as the updated DALI standard is still being published, there are certain fields that are proposed to be included in the future. Table 2 presents the mapping between the proposed data model and DALI 1.0 as well as 2.0.

Table 2: DALI and LBNL data model mapping

Data Element Name	DALI Specification & Enumeration
Group ID	Groups
Scene parameters	Scenes: int 0-15; Fadetime: .1sec -16 minutes as encoded octet.
Illuminance target level	NA
Device serial number	NA
Device firmware version number	NA
Device hardware version number	NA
Device/Luminaire Location	NA
Sensor Location	NA
Light source CCT	RGB, RGBWAF, xy
Sensor CCT	TBA
Time of day	NA
Individual Sensor Occupancy	Occupancy sense: Movement as bit; Occupied as 2 bits
Room Occupancy	TBA
Individual Daylight Sensor	NA
Individual PhotoSensor Levels	Photocell input: int 0-1023 lux
Illuminance level	TBA
LightLevel	Level: int 0-254; Fadetime: .1sec -16 minutes as encoded octet.
Luminaire Group Status	TBA
Room Zone Levels	Group: int 0-15
Relay Status & Control	Analog input
Device on/off state	Switch input
LightState	Level control
Dimmer Status and Control	Switch input
LightDim Level	Level: int 0-254; Fadetime: .1sec -16 minutes as encoded octet.
Preset Status and Control	NA
Room Preset or Mode	NA
Scene ID	TBA
Room DR Mode	Load Shed Condition: int 0-3
Device energy consumption	TBA
Power consumption	TBA

As can be seen, certain parameters (identified by “TBA”) are proposed to be added as part of the DALI 2.0 standard while others have not been specified in the existing standard.

Summary of Communication Standards Findings

The way DALI is structured as a protocol restricts its ability to be extended to newer applications in the connected lighting space. DALI 2.0 is intended to make adoption by wireless lighting systems easier with specific requirements for wireless control devices as well as sensors, however its market adoption cannot be assured. LBNL will continue to work with the ANSI committee and through it with the DIIA organization, which is also a member of the committee, to add the missing fields as part of DALI 2.0. The research team has also proposed the adoption of the open API by networked lighting control system (NLCS) manufacturers for improving the interoperability throughout the industry.

CHAPTER 3: Intuitive, Standardized User Interfaces for Networked Lighting Systems

Purpose and Scope

In parallel to, and complementary to, the efforts to develop the energy saving sensor-rich networked lighting controls detailed in Chapter 2, the research team also created content that could be the basis for a user interface standard for lighting controls. This could be used immediately by manufacturers in designing products, could be adopted at the U.S. national level, and eventually could be adopted internationally. The scope of this effort includes controls experienced by people in their ordinary home and work lives. Out of scope are professional controls, as might be used in theaters or others for which controlling lighting is a principal job function (though these could be designed in accordance with the common standard).

The premise underlying the effort is that consistent controls aid in humans understanding the capability and status of lighting controls they encounter, and being able to most easily express their preferences. As people are more likely to expend effort to gain more illumination than to get less, this should save energy. As consistent controls are no more expensive to manufacture than inconsistent ones, there should be no effect on manufacturing cost.

Technical standards have the characteristic that if the standard doesn't exist, it is impossible for a single manufacturer to implement or gain the benefits of the standard. User interface standards have this same feature.

Humans rely on user interface standards in many aspects of everyday life, from the symbols and colors on vehicle dashboards to the layout of phone keypads and more. Lack of these would incur costs, energy waste, and for vehicles, injury and death. Lighting has been remarkable in its lack of use of standards. While some conventions have at least national consistency such as that in the United States the "up" direction is generally used to switch a light on, the reverse is true in many parts of the world.

Problem Statement

Increasing lighting system complexity leads to user confusion

Conventionally, lighting was only on or off, so a single switch with two states was all that was needed for control. As each room had just a few distinct lights, the whole system of controls was fairly simple. Over time, the number of potential variables in how lighting may be controlled has grown, and now includes dimming, light color, occupancy sensing, daylight sensing, and scheduling. The number of controls that have multiple features, and their sophistication in being able to use them, is growing rapidly. In the absence of any common language for lighting controls to communicate their capabilities and status to the user, most remain opaque. Those controls that do include user interface elements do so in an ad hoc and inconsistent manner. Often the result is that the user gets less light or the wrong type of light for their needs. Even more often is that more light is delivered than is needed, wasting energy.

This effort builds on the concept of network communications between two digital devices. Communication between devices and human beings can be readily seen as an extension of this, as standards are required for communication to be successful. Languages are essentially communication standards, as are color coding of traffic signal lights, and much more. As we network ever more devices to each other, it is ever more important to effectively "network" people with the digital systems, through effective user interfaces.

In discussing the OSI (Open Systems Interconnection) model of networked communications, user interfaces are commonly called the "8th Layer" (the model itself having seven layers).

Key Innovations

This project has developed and proposed the world's first lighting control user interface technical standard. If successful, the terms and symbols in this standard could be as widespread as the symbols on automobile dashboards or the arrangement of numbers and symbols on the standard telephone keypad. It brings together some concepts and content that exist in current standards and products, as well as some content that is entirely new. Examples of the latter include a proposed new symbol for "occupancy," a new idea for how to conceptualize light temperature, and a symbol to embody that concept.

The attachments to the lighting control user interface standard report have the technical content of the research findings from surveying products, and a recommended user interface standard and rationale. This chapter focuses on the process underlying that content. That process begins before the project and extends after it; standards processes are years long and require ongoing commitment.

Pre-Project Activities

LBNL was able to engage in this project due to prior CEC-funded work on user interface standards. This began in 2000 with a project on power control, which can be summarized as "how we turn things on and off". At that time, there were individual user interface "elements" (e.g., symbols, terms, colors), but no overall standard on the topic to tie them together. In addition, the world was moving from a situation in which there were two basic power states (on and off) to many power states. That project concluded that there should be three power states, with sleep a state intermediate between on and off. The research culminated in a recommended standard on the topic. A follow-on project, also CEC-funded, enabled our work to be brought through the IEEE Standards Association (Institute of Electrical and Electronics Engineers) and emerge, two years later as IEEE 1621.

That initial work established the foundations for understanding user interface standards as an energy efficiency resource. It was clear that the principle could be extended to other domains of energy use, with lighting and climate control the two most obvious candidates. The approach is to essentially create a dictionary of individual elements with associated meaning. Symbols are the most obvious of these, but other elements can be terms, colors, physical mappings, sounds (and more recently audio input), haptic content, and critically, metaphor. A core example of metaphor is the use of "sleep" in the power control context which has an associated symbol, color, terminology, and facilitates people thinking and speaking of a device “going to sleep” or “waking up”. Collections of elements work together as units of meaning.

In 2009, the CEC funded a project for background research on the topic of a lighting control user interface standard. This project extensively reviewed existing standards and a wide variety of products. It concluded that there was no standard - national or international - directly on the topic, but a significant amount of generic user interface content that could be applicable. It also identified some initial categories in which to organize user interface information and a potential future standard. All this set the stage for the current project.

Project Activities

Survey

The first and biggest part of the project was to extensively survey and digest the content of user interfaces on products for sale today (Nordman et al., 2017a). This covered a wide range of devices for residential and commercial contexts, traditional and networked/connected, simple and complex, hardware-based or display-based, and more. Products from over 20 manufacturers were assessed. The list of topics has evolved slightly from the early work through this project. The list in this survey is:

- Lighting in General
- Scenes
- Switching (Static)
- Color Control
- Dimming/Brightness (Static)
- Shading Control
- Dynamic Control
- Other Topics

This survey provided the raw data that was part of the input to the later process of crafting a proposed standard.

Standards Organizations

A goal of the project was to craft content for a potential standard, and present it to a suitable standards development organization (SDO). This would serve several purposes, including giving the content much more credibility, engaging key manufacturers in the content, and providing a mechanism for periodic review and updating of the content.

Early on in the project we identified the National Electrical Manufacturers Association (NEMA) as the organization best suited to hosting the content resulting of this project. In principal, the content should be in an international standard, e.g., with the ISO (International Organization for Standardization, which covers a wide variety of standards), the IEC (International Electro-Technical Commission, which covers electricity and electrical devices in many respects), or CIE (International Commission on Illumination, which covers many aspects of lighting). The ISO and IEC have an extended set of standards that cover symbols, and there are several ISO standards on indicators and actuation. LBNL has tried to work with both organizations in the past but with almost no success. In general, one has to persuade the country as a whole to join a committee (which requires multiple companies, fees, and years of commitment to participate), and to regularly attend meetings, which are almost always outside the U.S. This is in general not feasible. While CIE would seem to be an obvious choice, no individuals or committees within CIE that find the UI topic of interest have been identified, so attempting to work with CIE on this topic would likely not succeed, and in any case, would also require considerable time and attending meetings outside the U.S.

Within the U.S., NEMA's membership covers the vast majority of the market in the U.S. for lighting controls, and it sponsors the ANSI Lighting Systems Committee (C137). No other U.S. organization is as related to controls design. C137 has on its membership all of the leading manufacturers of lighting controls in the U.S. Finally, NEMA staff encouraged participation.

The Illuminating Engineering Society (IES) could also host standards development, but it is mostly oriented to individuals who work on the science and application of lighting, rather than manufacturers. It does have a Light Control and Luminaire Design Committee, but conversations with representatives of the IES and NEMA, and many individuals, have always pointed to NEMA rather than the IES as the best host and no other likely alternative has been identified.

NEMA Standards Processes

The research team has been in contact with NEMA staff since early 2016, including periodic meetings at their offices, committee meetings, or conferences. Interactions with the C137 committee, which normally meets twice a year, have been as follows.

- In March of 2017 the team presented to the C137 committee remotely, to outline the possibility of and need for a user interface standard and request that the committee consider this.
- In August of 2017 the team presented the concept and the specific proposed content for a user interface standard in person. At that meeting, an ad hoc committee was formed to discuss whether a standards project should be started. This was the only meeting LBNL attended in person. Phoning into meetings was not always an option.
- The ad hoc committee met twice, the second time in early 2018, and voted 8-2 in favor of starting a project on the topic, the first step to creating a standard. This recommendation then went to the full committee.
- At the Spring 2018 C137 meeting the user interface topic was near the end of the agenda and by the time it came up a quorum was no longer present and no action was taken.
- At the Fall 2018 C137 meeting the topic did not come up because the meeting was closed after one day (usually they run up to three) due to severe weather (a hurricane) in the local area.
- At the Spring 2018 C137 meeting, it was again at the end of the agenda and a quorum was not present to take an action, but four company representatives volunteered to work with LBNL on preparing material needed to move the project forward at the next

meeting. As part of this LBNL will work with the volunteers to create "PINS" language as the basis for the project initiation proposal. There was a new staff person for the committee running this meeting, which may enable progress to occur more expeditiously.

Standards development is usually a slow process but this has been especially so. In addition to the hurricane, the most supportive person in August 2017 (who was actually chair of the committee) retired a few months later. Standards processes are not predictable in when they start, finish, or speed up or slow down. While this current project will come to a close before the next C137 meeting, LBNL intends to continue to participate. Many individual staff from lighting control companies have expressed support for the concept in discussions.

CIE

LBNL has monitored activities of CIE (International Commission on Illumination), the international standards body relevant to lighting, to see if there was any interest in the user interface standard topic. To date there has been none but it did seem clear that if there were to be any activity it would be within its Division 3: Interior Environment and Lighting Design. CIE is based in Austria, and usually meets in Europe or other places outside the U.S. In 2019, CIE is meeting in Washington D.C., and an abstract on our topic was accepted for this meeting. This will be after this project concludes, but LBNL intends to bring the lighting user interface topic to this meeting to see if international interest can be sparked. This would most likely be an activity subsequent to completion of consideration by ANSI/NEMA. Commonly standards are first developed at some national level and then moved to the international stage.

Proposed Scope, Content, and Rationale

This standard defines user interface elements for manufacturers to use in the design of lighting controls. It is applicable to hardware controls, software displays, and documentation. The proposed standard was created foremost for controls experienced by people in their ordinary lives, at home, work, or elsewhere. However, it may also be used for professional controls that are only used in the course of a job function (e.g., large building central controls or theatrical controls). The controls may be dedicated lighting controls, controls for many purposes (e.g., home automation systems), or controls with some other specific primary function (e.g., shading/lighting coordination with HVAC for efficient thermal comfort).

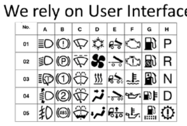
The standard covers the following topic areas: Lighting in General, Basic Switching, Brightness, Dynamic Control, Color, and Other Topics. The standard addresses visual elements (terms, symbols, and colors), dynamic elements (indication and actuation), audio elements (sounds and words), and tactile elements (identification and actuation). The standard does not cover ergonomic or safety issues that might be associated with lighting controls.

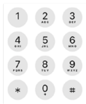
Prior to the August ANSI/NEMA C137 meeting, LBNL completed the "Proposed Lighting Control User Interface Standard" along with "Appendix III. Lighting User Interface Standard — Background and Development". The proposed standard was written in the form and language of a technology standard so that a standards committee with modest effort could adopt it. This also showed the proposal's practicality. It was assumed that any standards process would modify the proposal, perhaps to change some material, likely to drop some, and less likely to add some. Manufacturers were requested to provide comment but none did, and said that they would prefer to in the context of an actual official process.

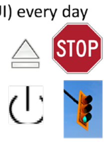
The proposed content and rationale are summarized in the following infographic, and more details on content and rationale are provided in Appendices III and IV.

Why?

- We rely on User Interface Standards (UI) every day


SAE J2402 2010 excerpt


Phone keypad



- **There is no UI standard for lighting control**
  - … but general UI standards are informative
- Lack of a UI standard
  - Impedes user understanding
  - Wastes energy
- Consistent UIs do not preclude innovation
- Consistent UIs do not increase costs

Plan

- Assess existing products
- Assess general user interface standards
  - Symbols, indicators, actuators, principles, …
- Develop content "topics"
- Use existing content when appropriate
  - From standards and products
- Develop new content when needed
- Bring to standards bodies and industry

Topics

Collections of UI content

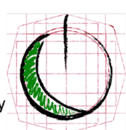
- General Principles
- Lighting in General
- Basic Switching
- Brightness
- Occupancy
- Daylight
- Color Temperature
- Other Topics

UI Modalities

- Visual
  - Terms
  - Symbols
  - Colors
- Dynamic content
  - Indication
  - Actuation
- Audio
  - Sounds
  - Words
- Tactile
  - Identification
  - Actuation

Power Control example

- Basic Concept: Power State
- 3 basic power states: On, Sleep, Off
- Standard mapping to indicator lights
  - **Green**, Yellow, **Off**
- Clear and self-consistent terminology
- Symbol usage | ◯ ⏻ ⏼ ☾
- Application details
  - Hibernate, accessibility, transitions, …



IEEE 1621: User Interface Elements in Power Control of Electronic Devices Employed in Office/Consumer Environments

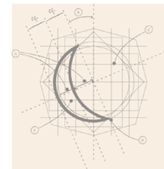
Next Steps

- Proposed standard content available:
  nordman.lbl.gov/lightui
- Revise proposed standard content
  - **Send in your comments**
- Possible U.S. standard – ANSI/NEMA C137
- Consider for International Standard
- Use in product design **now**

Proposed Content and Discussion

General Principles

- Define language of terms, symbols, colors, metaphors, ….
  - NOT how to use it
- Avoid or explain "secondary actuation" for ordinary tasks
- Use standard physical mappings
  - On/more:
    Up, Right, Clockwise, Away (from user)
  - Off/less:
    Down, Left, Counterclockwise, Towards (user)
- +, –, △ , ▽ , ◁ , ▷ for more/less



- Product designers choose elements and arrangement just as writers choose words to create sentences and paragraphs
- Symbols preferred to terms
  - Terms to be translated to local language
- Additional methods usually not explained or obvious
- Some countries would need to change
- Need to make symbols standard; with this meaning

Lighting in General

- Use IEC standard symbol – "Lamp; lighting; illumination"; "To identify switches which control light sources, …"

- Symbols on products diverse but related to standard symbol

Basic Switching

- Use "power state" | ◯ ⏻
- Use standard symbols – On, Off, Power

- Most switches unlabeled
- Words common in U.S.
- Symbols common outside U.S.
- Not "dimming" as underlying metaphor

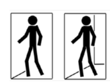
Brightness

- Use IEC standard symbol – "Brightness; brilliance"; "To identify the brightness control, for example of a light dimmer, a television receiver, a monitor, an oscilloscope.

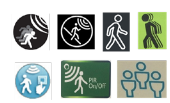
- Scale should match human perception
- Symbols for 'variable control' –

Occupancy

- Concept – for sensor, control, or controlled source
- This a proposed new standard symbol

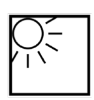


- Symbols not on products – on marketing materials



Daylight

- Concept – for sensor, control, or controlled source
- This a proposed new standard symbol



- Symbols not on products – on marketing materials
- Symbol used in box is "colour temperature, natural light"
- Box intended to indicate a window

Color Temperature

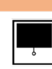
- Proposed metaphor is time, not temperature
- "Color Time"
  - Morning: blue/cool
  - Afternoon: yellow/warm
- These proposed new standard symbols

- Air/water temperature: cool is lower than hot
  - Cool to left; warm to right
  - Color temperature is backwards
  - This is/will be confusing; endlessly
  - Color temperature not experienced directly
- A different metaphor needed
  - Not too late to change

Color and Shading

- Color (existing)

- Shading (new)



Key Gaps

- Accessibility
- Scenes
- Speech
- Color selection

CHAPTER 4: Verifiable Performance for Networked Lighting Systems

Scope

Increasing lighting control system complexity, in terms of algorithms and networking, poses operational risks caused by incomplete specification, misconfiguration, or incompatibilities between system components. These problems range from the traditional under-/over-dimming and occupant annoyance to more systemic failures attributable to complex algorithms and communications. Lighting systems integration from multiple manufacturers carries a heavy "integration tax" for the labor needed to design, specify, custom program (during commissioning), and troubleshoot each building installation. The goal in this testing was to develop a new method for evaluating and specifying lighting systems' performance, to ensure that flexible, networked lighting technologies achieve their full potential. In conjunction with this purpose, the research team developed a set of evaluative metrics, and reviewed current technologies for their ability to offer this information.

To investigate these issues, particularly with respect to automated energy-reporting features from networked lighting controls systems, LBNL used the FLEXLAB® research facility to test several current technologies. Experiments were conducted in which systems were installed and addressed to controllable lighting loads, and commissioned to operate and dim lights based on various conditions. Lighting energy use was measured by the lab as a reference to compare against system self-reported energy usage. This allowed the research team to evaluate the lighting systems' ability to provide performance metrics (actual energy usage over time) useful for outcome-based code development and compliance.

Originally, the team set out to specify a software that could be developed to transform the event data implicitly collected by modern lighting controls into a stream of lighting energy use (kWh) data that continually tracks the real-time energy consumption of the lighting system at sufficiently fine temporal and spatial resolution. This single-software energy monitoring method was to be validated for accuracy by testing it in FLEXLAB's controlled laboratory environment. However, based on the process of setting up and carrying out lab evaluations of the lighting systems, it became evident that a single-software framework to interpret the reports from various systems was not workable or necessary for the task. Lighting control system manufacturers saw early results and enhanced their control system technology to monitor "real" energy rather employ fixture energy lookup tables. The systems' own energy reports were compared to reference measurements to determine suitability for performance testing and validation. This work will extend in future research, to evaluate the performance of current code-minimum lighting systems in relation to these metrics, and to provide the information and foundation to shift code development towards an outcome-based method.

Tasks

The following tasks were completed as part of this activity:

- Developed proposed lighting system performance evaluative metrics, and proposed a set of metrics applicable to whole building and lighting system level retrofit applications that can be used to determine the installed systems performance
- Evaluated several commercially available, networked lighting control systems to describe the types of data they produce in standard operation, and the interfaces for accessing these data.
- Software specification and development:
  - Developed a software specification that transforms event data implicitly collected by intelligent, networked lighting controllers into a stream of lighting energy use (kWh) data and other metrics that continually tracks the real-time, lighting system energy consumption at sufficiently fine temporal and spatial resolution.
  - Prepared a software validation test plan that describes the testing to be done at LBNL's FLEXLAB® facility to validate lighting monitoring system accuracy. Three lighting control systems were selected for validation testing.
- Developed a test method for verifying lighting monitoring software performance accuracy.
- Conducted the validation testing in FLEXLAB®.
- Prepared a validation testing report and protocol that summarizes the validation testing results conducted in FLEXLAB®, including a comprehensive framework for determining performance metrics for these lighting systems, along with a proposed testing protocol.

Topics and outcomes for further development

New performance metrics for lighting system

In building energy code requirements for commercial lighting systems, an outcome-based code model would move from lighting power density (LPD) prescriptions to energy usage intensity (EUI) prescriptions for different use cases and space types.

Lighting power density, or LPD (watts/ft^2) as the focus of building energy code requirement is an incomplete and imperfect option. Consider that a high-wattage lighting system that is rarely on, or is always operated at dimmed, or reduced power, settings (analogous to partial load performance of a chiller) may be less energy intensive than a lighting system with a lower "nameplate" wattage that is operated continuously at full load. Especially with the state of dimmable modern lighting technologies, the simplified concept of lighting power density as a catch-all lighting performance metric loses meaning.

A more effective metric for capturing the actual energy impact of a lighting system over time is energy usage intensity (kWh/ft^2/year). Like LPD, it is normalized to building area, but unlike LPD, the energy usage intensity of a system is not bound by the nameplate performance at maximum load, but rather reflects the actual operating characteristics of a system over time.

Annual EUI reflects the total energy usage over that timeframe without respect to simple installed power density totals.

The drawback with EUI historically as a prescriptive requirement was that energy usage of a system, post-installation and through time, was unknowable, at least not without significant measurement and verification effort. In-situ monitoring of a lighting system's performance, energy usage, or even simply operating hours, while useful for research and for the curious building manager, was hardly a practical option for code compliance. At best, energy usage could be estimated based on LPD and assumed operating hours (per year for example) but those estimates would be imperfect. On the other hand, with known quantities of light fixtures and known fixture areas, it has always been straightforward enough to calculate LPD for a new building or renovation project. Hence code's traditional reliance on the LPD metric as the figure of merit for lighting systems requirements.

Outcome-based code compliance through software validation and self-reporting

Traditionally lighting energy performance for a new lighting system has been estimated *ex ante*, based on lighting power density and various assumptions about operating hours. Modern networked lighting control systems however can provide much deeper insight into how and when lights in a building are used. With lighting endpoints networked together in a connected architecture that is supervised centrally, trending of operation and performance of components in the system and the system as a whole is possible. Baseline conditions can also be established, from which to determine improvements over, or adherence to, a future performance code level.

With the advent of energy reporting features from many networked lighting control systems, it is possible in theory to track lighting energy outcomes from a new lighting system *ex post*. If self-reported demand and energy usage from lighting systems is found to be reliably accurate (within an acceptable tolerance), building codes for lighting systems could move from the lighting power density prescription approach to an outcome-based energy usage approach; e.g., a maximum EUI allowance per space type. The lighting system performance as quantified by the system's energy reporting could constitute the means of verification for the purposes of code compliance. Policy makers, regulators, utilities, and end users would all be similarly served by reliable self-reporting, as all have an interest in knowing whether and how a new networked lighting system delivers on expected efficiency gains.

It is conceivable that the front-end software of networked lighting control systems could be equipped with simple energy reporting modules for code compliance that aggregate space types and report energy usage after system start-up. First year energy data reports for measurement and verification (M&V) contractors and regulators could be automated for each of the space types defined in code and present in the building; e.g., conference room, lobbies, classrooms, large and small offices, etc. With the facilitation of energy self-reporting, ASHRAE 90.1, IECC, and CA Title 24 space-by-space LPD requirements could be transitioned into EUI requirements. For example, consider Title 24 space-based lighting power determinations. The Area Category Method lists LPD values for various space type; for example, Corridor, Restroom, and Stair, (0.6W/ft^2), Office over 250 ft^2 (0.75W/ft^2); Offices less than or equal to 250 ft^2 (1.0W/ft^2); and

Lobby (0.95W/ft^2). This method could be revised to focus on the actual performance of the lighting systems in those spaces if lighting energy usage in those spaces could reliably be determined through networked lighting controls' self-reporting. Whole-building LPD as a compliance method could also be transitioned to EUI requirements or allowances.

Built-in energy reporting modules could include different categories for the various building codes that may apply to a project. Parameters like room cavity ratio and daylighting zone designation could all be used by the software for compliance calculations. These types of simple dynamic features would tailor energy self-reporting to the building characteristics and code requirements that flow from them. Modules for carrying out the functional testing requirements that are already in Title 24, IECC and other codes for lighting controls, could equally be set up in networked lighting controls software to streamline compliance and enforcement.

Energy reporting requirements in current networked lighting controls specifications

The Design Lights Consortium (DLC) defines a networked lighting control system as "consisting of an intelligent network of individually addressable luminaires and control devices, allowing for application of multiple control strategies, programmability, building- or enterprise-level control, zoning and rezoning using software, and measuring and monitoring." https://www.designlights.org/workplan/networked-lighting-controls-specification/

The DLC's lighting controls specification includes details on energy reporting from networked systems. Energy reporting capabilities had not previously been a required feature set in order to meet the specification, but that is changing this year. Per the latest published version of the specification (V3.0), energy reporting is defined as "the capability of a system to report the energy consumption of a luminaire and/or a group of luminaires. The use of energy monitoring on dedicated lighting circuits is also acceptable." The current version of the policy clearly lays out the future direction of the specification, which will transition energy reporting from an optional to a required feature. The means of energy reporting will then transition from either measured or calculated approaches being acceptable to a measurement-only approach, with an option for calculated reporting if a standard that guarantees accuracy is developed in the meantime.

- "In V4.0, to be released June 1, 2019, Energy Monitoring will become a required capability. Manufacturers will report the method of monitoring (direct or calculated), and the accuracy of measurement that is direct. In V5.0, to be released June 1, 2020, calculated methodologies will not be accepted as meeting the energy monitoring requirement unless supported by a new ANSI standard that specifies the accuracy of the methodology. If an ANSI standard to support the methodology is not developed, then only direct measurement methods will be accepted and manufacturers will self-report the accuracy of the direct measurement method."

Future metrics and dimensions of lighting quality

While not expressly related to tracking energy performance for code compliance verification, the research team tracked other metrics and dimensions of lighting performance evolving in the marketplace due to technological and research innovations. For example, commercial tunable white LED fixtures now available allow for operating profiles that adjust intensity and color through the day to provide visual comfort and increase health benefits while saving energy. These systems will often be implemented with networked lighting controls capable of effecting new lighting control strategies. Per the DOE, "color-tunable LED[s] are a… growing product category. Beyond energy efficiency … potential benefits include improved health and well-being… there is reason to believe that color-tunable [LEDs] will gain market share." https://energy.gov/eere/ssl/led-color-tunable-products.

Tunable lighting systems are intended to improve visual and health benefits while continuing to enable energy savings; coupled with connected controls they can enable dynamic lighting strategies, including DR opportunities. As this emerging technology is adopted, it is critical that designers, utilities, and program implementers understand the strategies that provide visual and health benefits for least energy cost.

However, the impacts and benefits of tuning color and intensity in buildings, while not yet fully developed as design criteria for lighting systems, will eventually require the introduction of additional lighting quality dimensions to building codes. Similar to the outcome-based energy intensity approach, these lighting quality metrics will most likely have time-variant components and will therefore require some level of monitoring and/or self-reporting. In other words, a prescriptive constant unit (such as LPD) will probably not be appropriate for health and well-being lighting strategies, which will almost certainly involve varying lighting intensity, and probably spectral content, through time, over daily and perhaps seasonal periods.

Laboratory testing of advanced networked lighting controls systems in FLEXLAB®

Objective

The goal of the FLEXLAB® experiment was to operate three advanced networked lighting controls systems with energy reporting capabilities (measured or calculated), primarily to compare reported lighting energy use from the controls system, to FLEXLAB®-measured lighting energy. The project team installed two lighting systems in a test cell side-by-side and operated those systems for two weeks with various operating parameters detailed below. The project then evaluated another networked lighting system; the existing dimmable lighting system and networked controls in the FLEXLAB® 4th-floor Lighting and Plug Load testbed. Similar to the other test, FLEXLAB® measured data was compared to energy reporting from the testbed lighting controls system.

The three networked lighting systems tested in FLEXLAB® facilities for this effort were:

- Fifth Light (Cell 1A)

- Enlighted (Cell 1A)
- Wattstopper (4^{th}-floor testbed)

Lighting and controls systems details

1. Fifth Light lighting controls system
    - Enterprise controls cabinet and server
    - 2-wire (DALI) network between fixtures, sensor, controls cabinet and server
    - 2 row, six fixture segments
    - 2 X 12’ pendant fixtures (4’ controllable sections)
        - 1 X LED
        - 1 X fluorescent (dimmable T8)
    - Ceiling – mounted Photosensor
2. Enlighted lighting controls system
    - Controls server and laptop
    - Network switch and Gateway
    - 2 X 4’ LED pendant fixtures with embedded sensors and controls
3. WattStopper Digital Lighting Management system, with dimmable T5HO fluorescent fixtures
    - Controls and fixtures already installed in Lighting and Plug Load Testbed
    - 2 X 4’ dimmable T5HO direct/indirect pendant mounted

All fixtures were powered by above-ceiling outlets that were individually monitored over time by the FLEXLAB® data acquisition system. The layout of the test setup for systems one and two in FLEXLAB® cell 1A is illustrated in Figure 22. Photos of the setup are presented in Figure 23.

Figure 22: Test setup for testing Systems 1 and 2

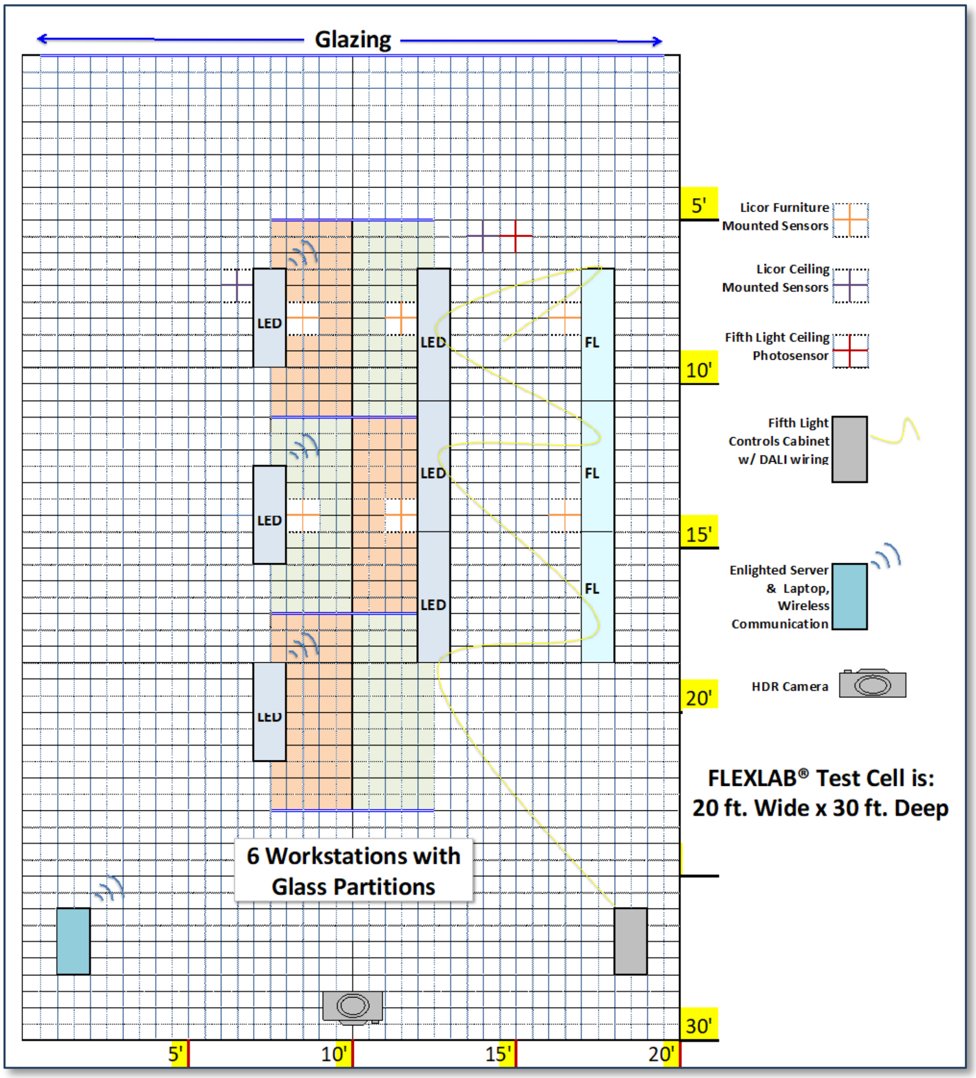


Figure 23: Photos of test setup in FLEXLAB

Test Operation

- FLEXLAB® 1A Experiment (Fifth Light and Enlighted): Aug 28 – Sept 10, 2017.
    - Daily operation of fixtures, and collection of reported energy and lighting data from controls front-ends and from FLEXLAB® data acquisition system.
    - Scheduled operation 7AM – 7PM; 12 hour per day on/off cycle with daylight dimming.
    - Both systems self-reporting on lighting energy as well as continuous energy monitoring via FLEXLAB®.
    - An array of daylight harvesting protocols run during test period
- FLEXLAB® Lighting and Plugload Testbed Experiment (WattStopper DLM): Feb 2019.
    - Continuous operation of fixtures in one cubicle office; pushing different dimming signals to the lighting load periodically, and collection of reported lighting data from BACNet server via python script and from FLEXLAB® data acquisition system.

Data collection

The power and energy consumption data from the three networked lighting control systems were directly collected from each system's energy reporting software front-end. The reference data for power and energy use was collected using the FLEXLAB® data logging system.

Figure 24 shows a plot of measured reference data from FLEXLAB® for the two lighting control systems tested in parallel in cell 1A. Figure 25 shows the reference measured data for the third system, evaluated in the FLEXLAB® Lighting and Plug Load Testbed.

Figure 24: Plot of FLEXLAB® measured lighting power data for test of Fifth Light and Enlighted networked lighting control systems

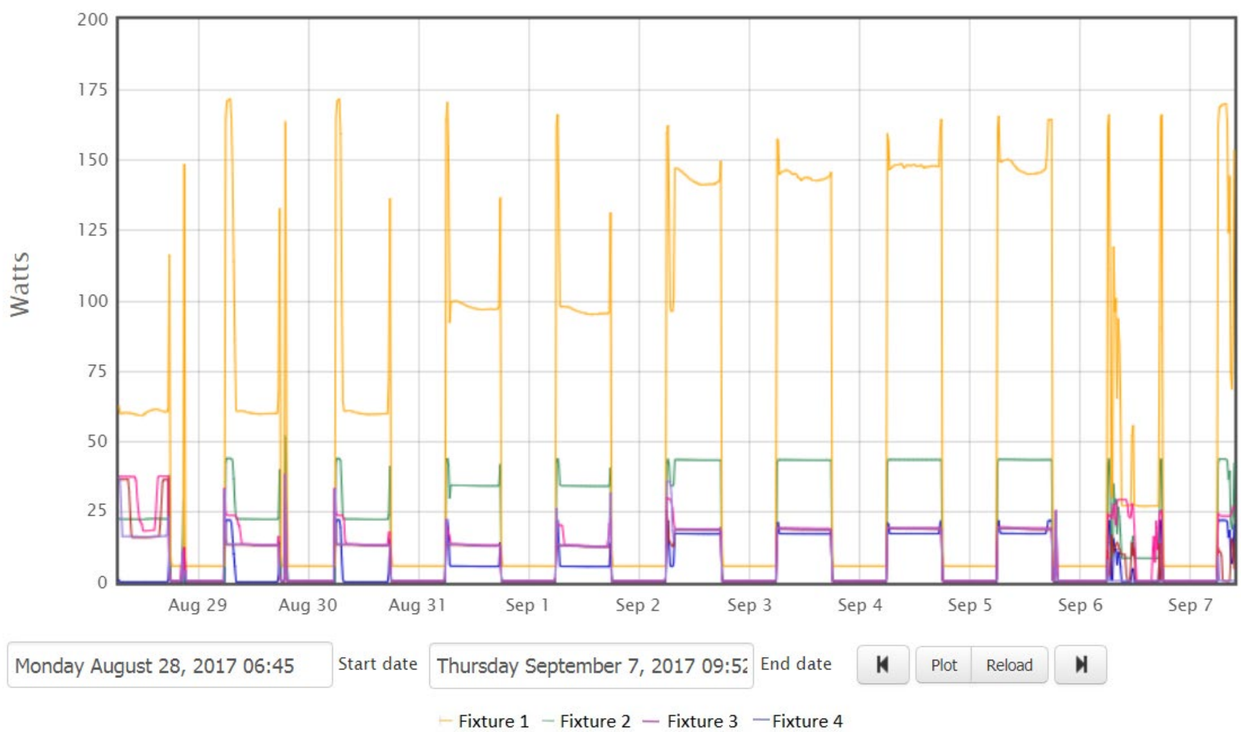
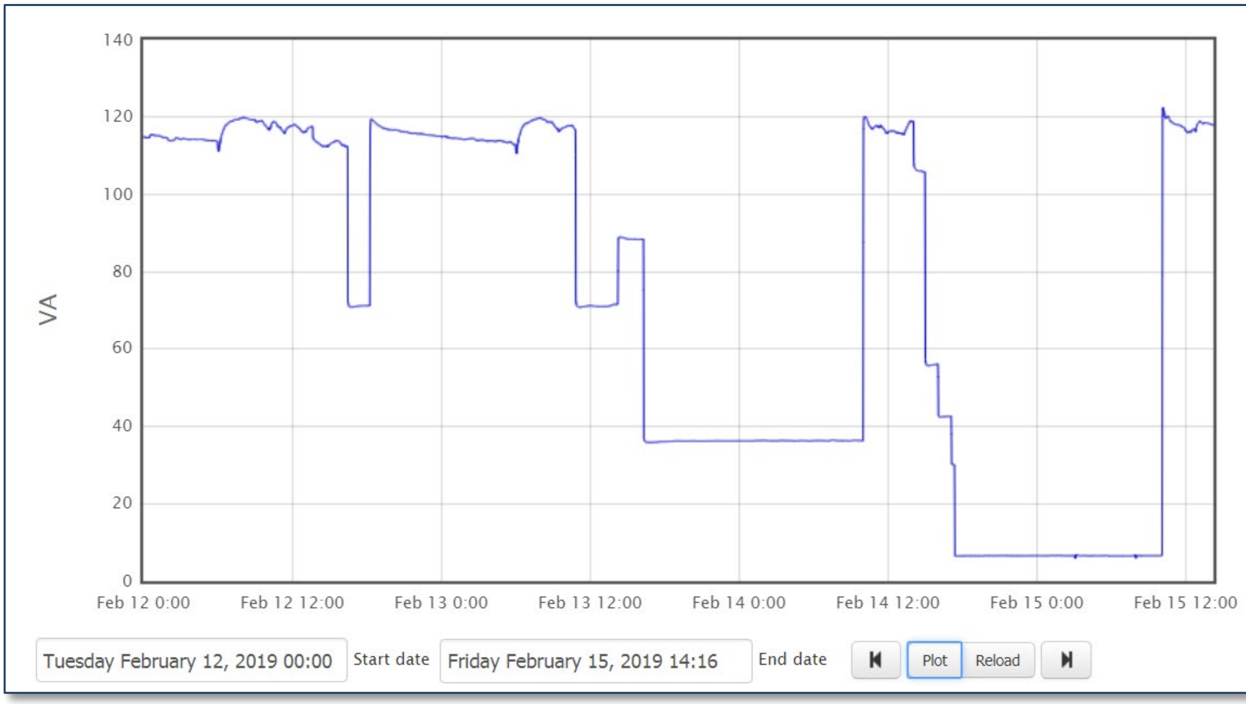
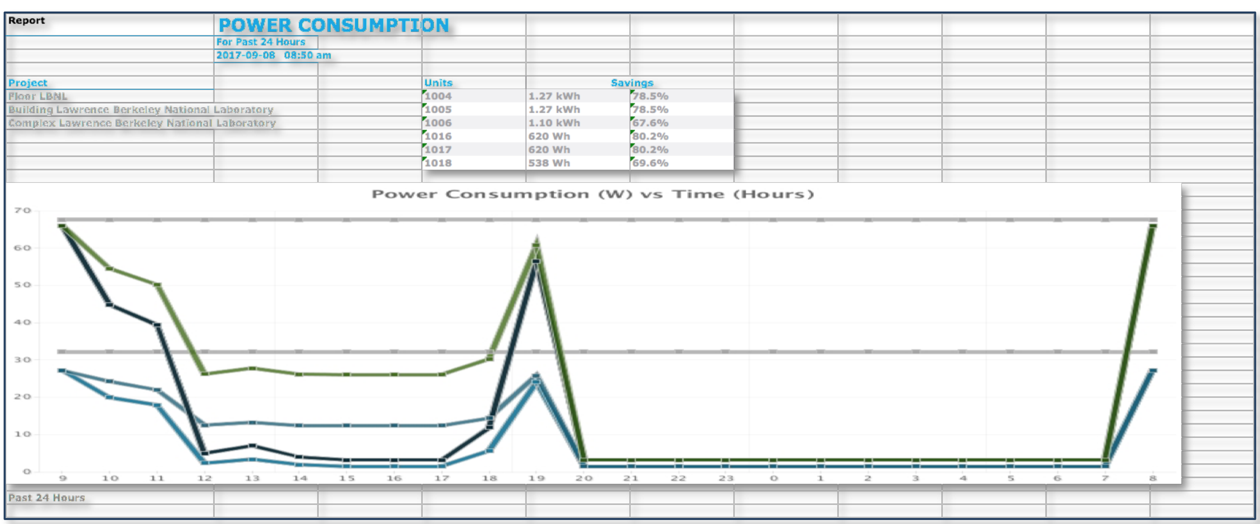


Figure 25: Plot of FLEXLAB® measured lighting power data for the Lighting and Plug Load test of WattStopper DLM networked lighting control system



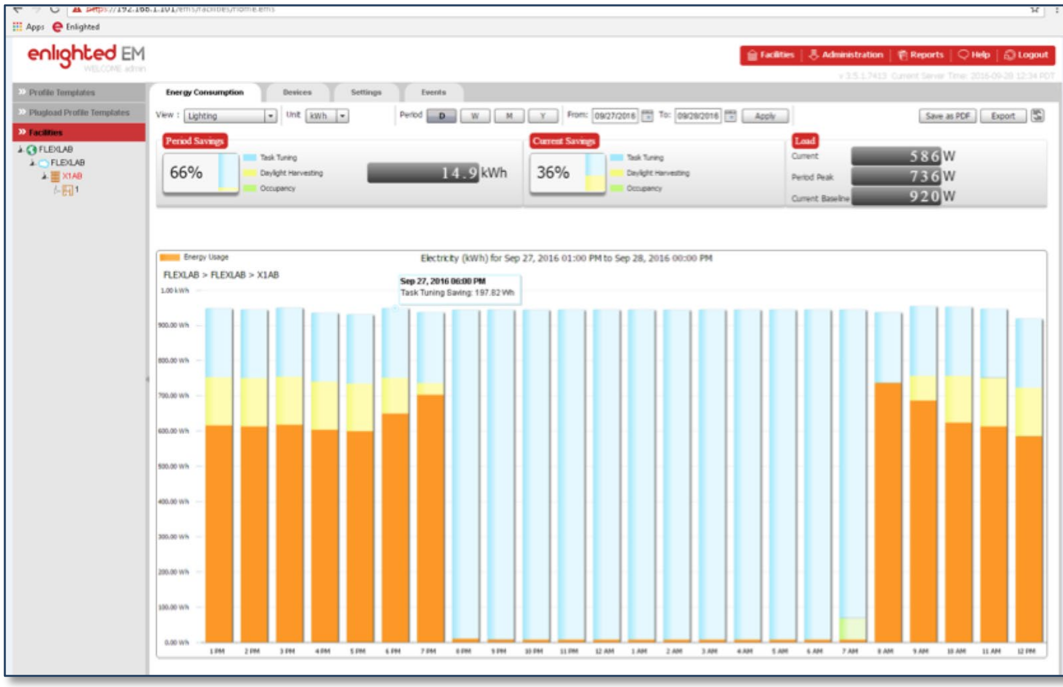
The Fifth Light system evaluated in the 1A test provides energy data based on a calculated method; in other words, the system does not directly measure energy throughput from controller to light fixture but calculates it based on assumptions regarding lighting load at different control conditions. Below is a screen shot of energy and power reports from the system; file data outputs are rows of data for the last 24 hours.

Figure 26: Screen capture of Fifth Light energy report



The Enlighted system, which was tested in the 1A experiment, provides energy data based on a measured method; the system has power monitoring circuitry on each controller to measure throughput to connected loads. The software provides columns of energy data as well as graphical plots of time-series usage, as displayed in the screenshot below.

Figure 27: Screen capture of Enlighted Energy Manager reporting interface



Finally, the WattStopper DLM system, which was evaluated in the Lighting and Plug Load testbed, provides data via a measured method as well, with power measurement circuitry on each room controller. For this system, a custom method of retrieving energy data was developed. Lighting power data was collected from the network bridge and room controller via BACNet protocol:

1. Connect to the BACNet network
2. Get the BACNet device ID of the particular room controller
3. Python script running on server connected to BACNet router and DLM system polls the register of the room controller where lighting power value is stored and writes value to file.

Analysis and results

The analysis of the data collected during the FLEXLAB® experiments is presented below. The overall goal of the analysis was to evaluate the difference between reported lighting energy from the networked lighting controls systems and FLEXLAB® measured lighting energy as the reference. This then helps determine whether reported energy from networked lighting controls is a reliable measure for use in validation and compliance, such as what would be required for the outcome-based lighting code approach.

The accuracy of energy reporting from systems that measure power for connected lighting loads (systems 2 and 3, with integrated measurement circuitry in the controller or on the lighting circuit) is compared to a system (system 1) that relies on inputs and assumptions during setup to calculate reporting energy values, to determine which methods are reliable enough for code validation.

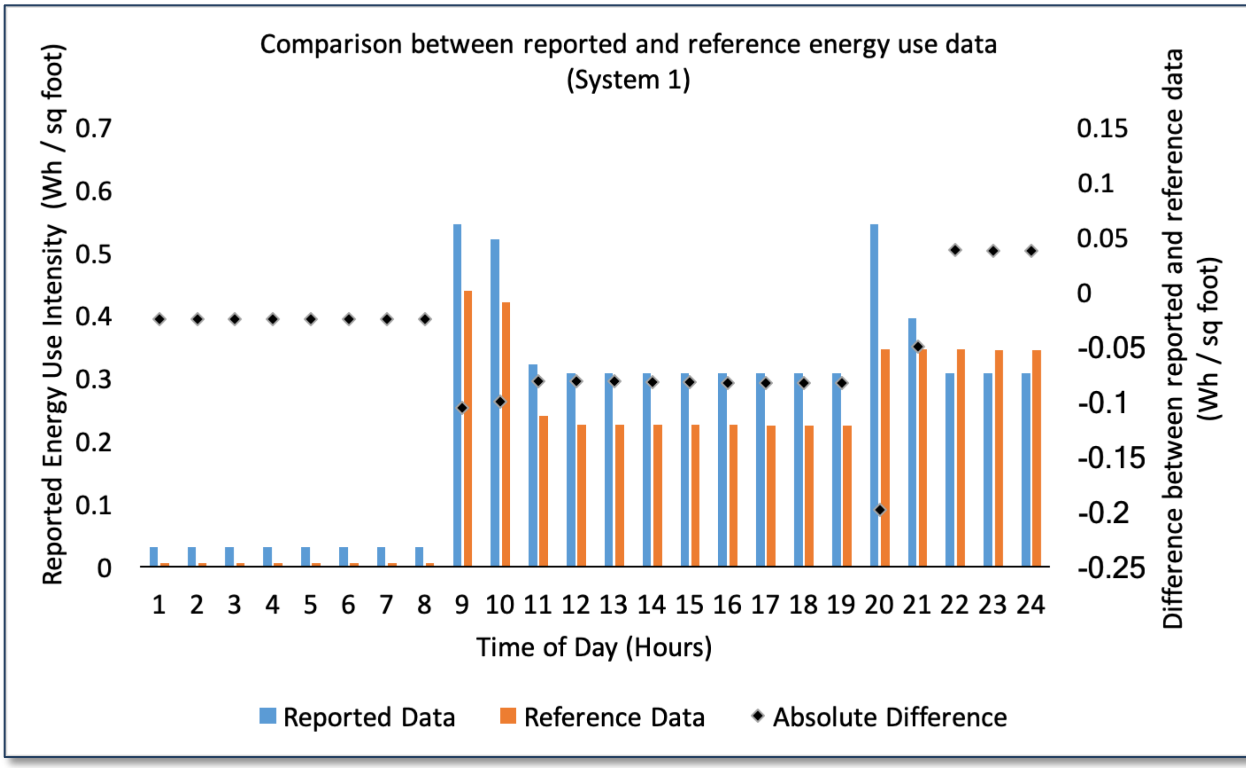
One day of hourly averaged data for each system test is presented here. The three systems were operated for several days over different conditions, but the hourly averaged data are shown to simplify the comparative analysis. Systems varied somewhat in the format of reported data, so data for all three were normalized to a common energy metric, watt-hours/ft^2, based on reported power or energy divided by an area derived from the experimental set-ups. The conversion of the data to an EUI metric is critical for outcome validation wherein a prescribed energy budget for a space type would be compared to energy usage over time as reported by the controls system.

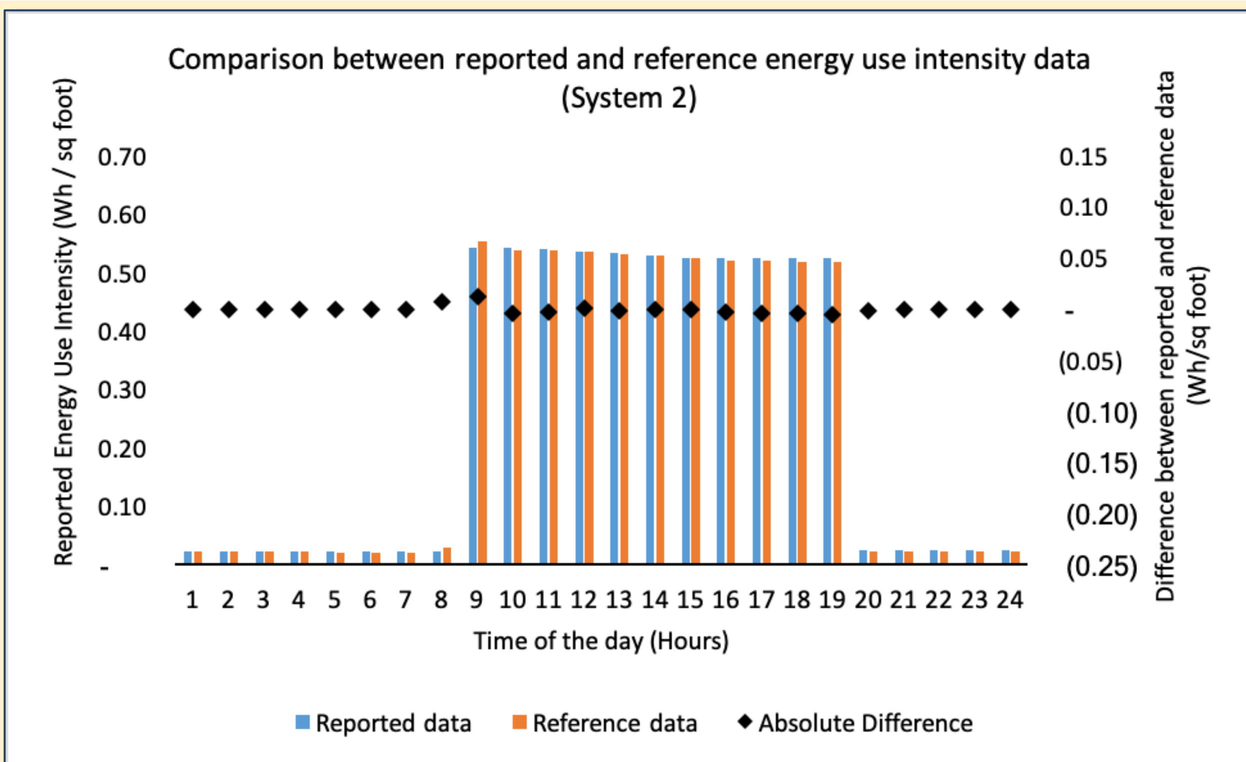
The quantitative outcomes from the three systems tests are illustrated in the plots below. System 1 relied on user inputs during commissioning to calculate the energy usage values that were reported by the system software. In the test the nameplate full power wattage of the LED fixtures controlled by the system was entered into the commissioning software - this step is crucial, as incorrect assumptions about connected lighting load almost guarantee erroneous energy reporting. Systems 2 and 3 measured connected loads directly in order to perform energy reporting. The direct measurement approach mitigates the risk of user errors during commissioning that results in energy reporting errors down the line is mitigated.

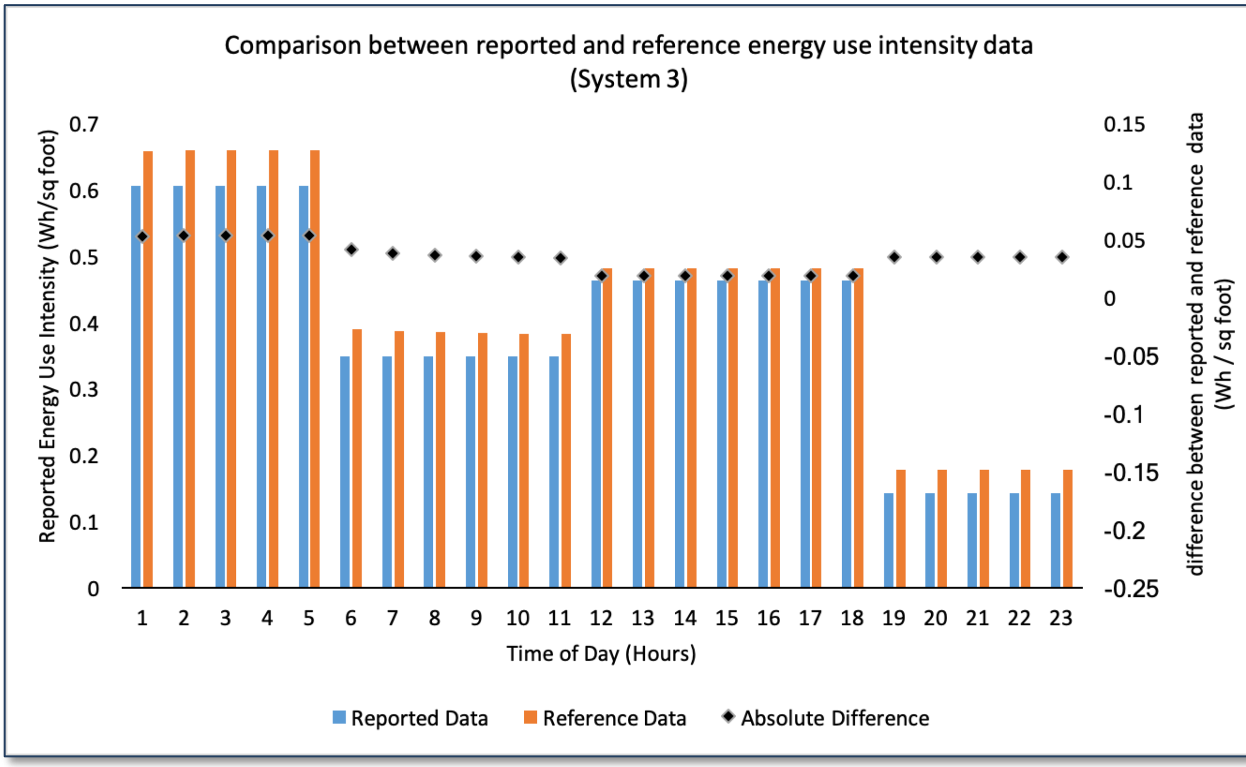
As shown in Table 3, one of the networked lighting systems that measures energy data for reporting purposes (system 2) does reliably report lighting energy usage. The data flowing from this system would likely serve as a good basis for monitoring and reporting energy usage over time. The other system that measures lighting load rather than calculating it provides a report with daily error (defined here is difference between measured and reported energy divided by measured daily energy total) between 5% and 10%. It is not clear whether this level of accuracy would be considered reliable for code compliance validation.

In contrast to the two systems that measure energy, the one that calculates it based on inputs during commissioning provides an energy report with a high daily error; in this case, the reported energy value for the day was over 25% greater than the measured value as shown in Figure 28. This discrepancy means that the reported energy is most likely not accurate enough for code compliance validation. The discrepancy could be either worse or better if different input assumptions were entered during commissioning. The risk is that this step is not performed properly, and that even if it is, the calculation method misses other factors about actual performance (fixture dimming behavior at different control signals for example).

Figure 28: Comparison between reported and reference data from Systems 1, 2, and 3







The energy monitoring methods of the three systems vary; in general, the measurement-based approach is more reliable, and therefore preferred for validation purposes. Based on this work, it does appear that networked lighting controls if designed and installed properly can be used for determining energy performance of lighting systems for outcome-based code. Reliability is not guaranteed however, as the variations in daily errors among the systems shows. The accuracy of a system's energy reporting feature should be verified prior to its use as a means of validating energy performance over time.

Table 3: Networked Lighting Control System energy reporting data compared to reference measurements

	Reference Energy Data (Wh/ft²)	Reported Energy Data (Wh/ft²)	Daily Error: reported - reference (Wh/ft²)	Daily Error / Daily Total (%)
System 1 (calculated)	4.66	5.95	1.29	27.7%
System 2 (measured)	6.10	6.13	0.03	0.5%
System 3 (measured)	9.86	9.07	- 0.78	-7.9%

Chapter 5: Technology Transfer

Overview

Transferring and disseminating technology and concepts from the project to a wider audience of stakeholders was a foundational goal. At the outset, a technology transfer plan was drafted, outlining strategies and tactics to be implemented in support of knowledge transfer from the project's achievements to the stakeholders and entities addressing the large, nonresidential customer segment, and to help promote the vision and potential of energy savings through advanced lighting and control technologies for the public good.

Technology transfer activities included formal and informal outreach, meetings, and conversations at academic, research, and industry events and conferences, as well as presentation of papers, findings and research outcomes at various symposia. Project team members maintained contacts and communications with stakeholders, industry groups, and a broad audience of beneficiaries.

The networked lighting project presented posters at the 2018 and 2019 EPIC Symposia. The 2019 poster is shown in Figure 29 below. A project website was also created in order to provide a convenient place to find material such as our research reports and standards proposals; http://lighting.lbl.gov/. The website includes the logo developed for the lighting control user interface standard, shown in Figure 30.

Figure 29: EPIC 2019 Symposium poster

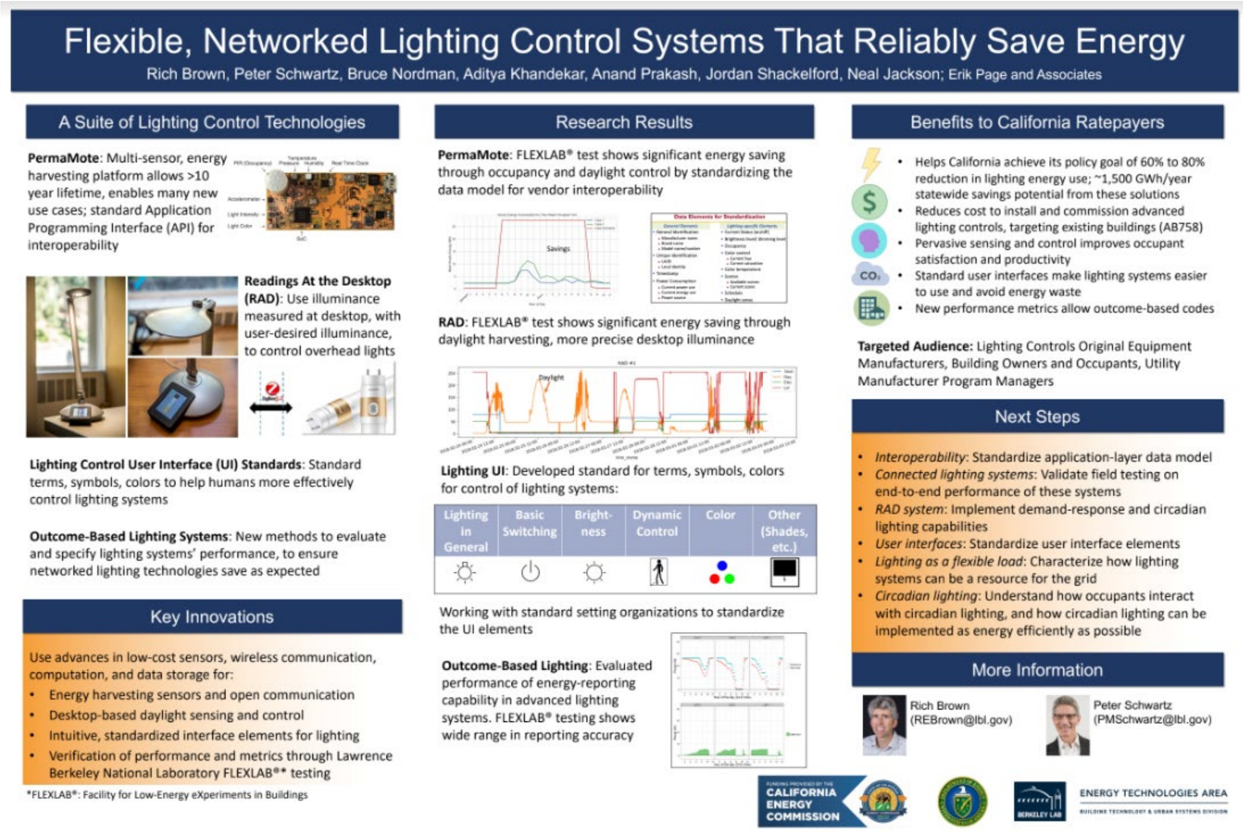


Figure 30: Lighting control user interface standard logo

Outreach, Presentations, Posters, and Papers

- Presentation on some of this project's research efforts to global semiconductor IP company ARM at a meeting March 30, 2017 (*Developing Flexible, Networked Lighting Control Systems that Reliably Save Energy Task 3 – Task Ambient Daylighting Data-Driven Daylighting Control*).
- Presentation on project's research efforts to leading networked lighting controls company Enlighted; including to Tanuj Mohan, CTO; Evan Petridis, Chief System Architect; and Chip Poland, Director of Utility Programs.
- Informal outreach at Lightfair 2017 and 2018 to support the project including meetings with industry stakeholders and suppliers (no official public presentations at these).
- Outreach at Strategies in Light conference and tradeshow, including a March 2016 presentation. This event is second only to the annual LightFair conference in attendance, and being in Santa Clara was cost-effective to attend.
- A paper was presented at the 2017 Energy Efficient Domestic Appliances and Lighting (EEDAL) conference. While EEDAL had previously always been held in Europe, for the first time it was held outside, conveniently in Irvine, California. The project team presented the paper *A Language for Light: A User Interface Standard for Lighting Contro*l (Bruce Nordman, Saikiran Dulla, Margarita Kloss, Lawrence Berkeley National Lab).
- Monthly briefings with DOE's Advanced Lighting Controls stakeholder call
- Poster presentation at the Semiconductor Research Corporation (university-research consortium for semiconductors and related technologies) TECHCON September 2018 conference in Austin TX, of PermaMote concept, features, design, and future work (*A Long-Lifetime Sensor Platform for a Reliable Internet of Things*) by Embedded Systems Research of UC Berkeley's Electrical Engineering and Computer Sciences.
- Published paper by UC Berkeley researchers on the energy harvesting and sensing techniques embodied in the PermaMote design, *Reconsidering Batteries in Energy Harvesting Sensing*; presented to stakeholders at ENSsys 2018; the 6th International Workshop on Energy Harvesting and Energy-Neutral Sensing Systems; November 04, 2018 in Shenzen China.
- A research paper on the benefits of battery storage as deployed in PermaMotes, over capacitors, for energy harvesting sensors, *Capacity over Capacitance for Reliable Energy Harvesting Sensors*, was published by UC Berkeley researchers for IPSN 2019, April 16–18, 2019, Montreal, QC, Canada. The International Conference on Information Processing in Sensor Networks (IPSN) is a leading annual forum on research in networked sensing and control, bringing together researchers from academia, industry, and government.

- A poster on the PermaMote technology was also presented at Secure Internet of Things Project (SITP) in June 2018, as well as at the Computing On Network Infrastructure for Pervasive Perception, Cognition, and Action (CONIX) Annual Review in 2018.

Standards and Data Model

Along with developing an open API for facility managers and owners to extend the reach of wired lighting systems, the research team developed a reference data model that could be used to communicate between existing lighting systems and low cost sensors. LBNL has been involved in ANSI Committee C137, which is in the process of creating a standard for lighting control systems. As part of the committee's work, LBNL has been participating in the development of a standard data model that will be a part of the eventual standard. The project team also created a mapping between the proposed data model with the updated DALI standard, which is still being developed. LBNL will continue to work with the ANSI committee and through it with the DIIA organization, which is also a member of the committee to add the missing fields as part of DALI 2.0 as well as to propose the adoption of the open API by NLCS manufacturers for improving the interoperability throughout the industry.

A number of activities were undertaken in the course of this project to bring the idea and content of the lighting control user interface standard developed by the project team to relevant stakeholders (see Outreach section above). The Lighting Control User Interface Standards survey results have also been shared with NEMA C137 Lighting Systems Committee.

CHAPTER 6: Benefits to California

Networked lighting controls systems hold the promise of unlocking significant new value by capturing detailed environmental and device level sensory information. They can also implement strategies to reduce energy consumption and manage building lighting load without negatively affecting lighting characteristics, such as dim level or color, so precisely that user comfort is not affected. Overall benefits related to project outcomes include:

- Helping California achieve its policy goal of 60-80% reduction in lighting energy use; an estimated ~1,600 GWh/year statewide savings potential from these solutions.
- Reducing cost to install and commission advanced lighting controls in existing buildings (AB758).
- Pervasive sensing and control improves occupant satisfaction and productivity.
- Standard user interfaces make lighting systems easier to use and avoid energy waste.
- New performance metrics allow outcome-based codes.

On lighting energy savings, Williams, et al. (2012) found that advanced lighting controls using a combination of occupancy, tuning, and daylighting typically saved 38% of lighting energy use, whereas the best performing systems had close to 60% energy savings. The technologies analyzed and assessed in this research project will make it much more likely that lighting control systems performing at the upper end of that savings range will be adopted, leading to an incremental 20% energy savings by these advanced systems (above the 38% average savings from advanced lighting controls cited above). In addition, the lower system cost through lower-cost components and reduced installation costs should lead to higher market penetration. Taken together, at these assumed savings levels, these advanced systems can save about 1,600 gigawatt-hours (GWh) per year statewide in the commercial building stock if eventually adopted in all office floorspace (assuming total indoor commercial lighting consumption of about 26,000 GWh/yr, about 8,000 GWh/yr for offices, and 20% incremental savings in offices), at an annual value of about $200 million ($0.12 to $0.14/kWh). Additional savings are achievable through different DR strategies as will be documented in the project research products.

This project also directly supported technology development and innovation in California. Research efforts spurred novel lighting control systems R&D by California researchers, students, and entrepreneurs. The RAD lighting controls system continues to advance in R&D efforts today, with National Institute of Health – funded lighting and wellness research underway in collaboration with the Lighting Research Center of Rensselaer Polytechnic Institute, and DOE SBIR – funded research to refine control methods and evaluate HVAC interactions. As this technology matures and commercializes, benefits will include CA jobs and energy savings opportunities. Likewise, the Permamote technology development supported by this project included robust collaboration with graduate school research efforts at UC Berkeley. The self-powered wireless sensors produced through this effort show promise for future development and commercialization.

CHAPTER 7: Summary and Future Research Directions

Overview

Key project innovations arising from the research include using advances in low-cost sensors, wireless communication, computation, and data storage for:

- Energy harvesting sensors and open communication
- Desktop-based daylight sensing and control
- Intuitive, standardized interface elements for lighting
- Verification of performance and metrics through LBNL FLEXLAB® testing

The researchers have several planned or pending projects which will build on the outcomes of this project. These include:

- **Demand Response Capability**: Southern California Edison will be supporting a research and field-testing effort that will explore adding demand response capabilities to the RAD controller. This project would involve software modifications to the existing RAD controllers and a field test of at least 30 RAD controllers.
- **Smart Grid Integration**: The Department of Energy will be funding a major research and development effort focused on utilizing the RAD controller to support smart grid systems. This project will involve major hardware and software updates to the RAD controller and the new RAD controllers will eventually be evaluated in LBNL's FLEXLAB® facility.
- **Interoperability**: Standardize application-layer data model (ANSI/NEMA C137 Lighting Committee).
- **Connected lighting systems**: Need validated field testing on end-to-end performance of these systems
- **RAD system**: Implement demand-response and circadian lighting capabilities.
    - The RAD technology founder has leveraged the developments from this project to get support from the DOE SBIR program, for which a successful Phase I project has already been completed and Phase II funding is being sought.
- **User interfaces**: Standardize user interface elements (ANSI/NEMA C137 Lighting Committee).
- **Lighting as a flexible load**: Characterize how lighting systems can be a resource for the grid.
- **Circadian lighting**: Understand how occupants interact with circadian lighting, and how circadian lighting can be implemented as energy efficiently as possible.

Sensor-Rich Networked Lighting

Advanced lighting controls are rapidly evolving, with wireless communications, embedded sensors, data analytics, and other features all integrated in new systems to optimize building systems in real time. Through this project, promising new networked lighting controls solutions were developed with dense sensor packages that could be deployed in the built environment to more accurately represent conditions, thereby providing better control points.

Results include the low-cost sensing, distributed intelligence and communications platform, the PermaMote self-powered, sensor and controller for lighting applications and the Readings-At-Desk (RAD) system, using illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights.

Functional testing of these systems yielded generally positive results; the technologies controlled lights as intended through the sensor inputs, programming, and wireless protocols used. Field evaluations of both systems proved viability in actual occupied office environments also. It is expected that these technologies will continue to develop through further research efforts and eventually transition into commercial viability.

In addition to the project team's technological innovations, the research team developed a reference data model that could be used to communicate between existing lighting systems and low cost sensors. LBNL has also been engaging with the ANSI Committee C137, which is in the process of creating an ANSI standard for lighting control systems. LBNL has been participating the development of a standard data model that will likely be a part of ANSI's standard. Lighting control standard DALI 2.0, currently under development, is intended to make adoption by wireless lighting systems easier with specific requirements for wireless control devices as well as sensors. LBNL will continue to work with the ANSI committee to add to DALI 2.0 as well as to propose the adoption of the open API by NLCS manufacturers for improving the interoperability throughout the industry.

Intuitive Standardized Interfaces

Consistency in user interface element used in lighting controls will make them easier for people to understand and use, and so easier to match desired light to what is provided. This can avoid supplying more light than needed and so save energy. The way such problems are normally solved in products and devices is to create a standard. This project has come up with proposed standard content and delivered it to the appropriate body to take up. The content was derived from extensive analysis of existing standards for user interfaces as well as examination of the controls found on many diverse products in the market.

More work is needed to bring the content through the standardization process. There are also issues for the topic for which solutions were not developed in the project, such as control of light color in general and of lighting "scenes". The latter in particular could be a tool to save significant energy so that progress on this would help California achieve its energy policy goals. Finally, there should be work in a few years to assess the current state of controls, to see how they have evolved since this research, to guide updates to the standard.

Standards development is usually a slow process but this has been more slow than most. Standards processes are not predictable in when they start, finish, or speed up or slow down. While this current project will come to a close before the next ANSI C137 meeting, LBNL intends to continue to participate. Many individual staff from lighting control companies have expressed support for the concept in discussions.

Verifiable Performance

With the advent of energy reporting features from many networked lighting control systems, and from the FLEXLAB® study of several systems, we found it is possible to track lighting energy outcomes from a new lighting system *ex post*. If self-reported demand and energy usage from lighting systems is reliably accurate (within an acceptable tolerance), building codes for lighting systems could move from the lighting power density prescription approach to an outcome - based energy usage approach. The lighting system performance as quantified by the system's energy reporting could constitute the means of verification for the purposes of code compliance.

The energy monitoring methods of the three systems studied varied; in general, the measurement - based approach was more reliable, and therefore preferred for validation purposes. Based on this work, it does appear that networked lighting controls if designed and installed properly can be used for determining energy performance of lighting systems for outcome - based code. Reliability is not guaranteed however, as the variations in daily errors among the systems shows. The accuracy of a system's energy reporting feature should be verified prior to its use as a means of validating energy performance over time.

Policy makers, regulators, utilities, and end users will all be well served by reliable self-reporting, as all have an interest in knowing whether and how a new networked lighting system delivers on expected efficiency gains. Networked lighting control systems could be equipped with simple energy reporting modules for code compliance that aggregate space types and report energy usage after system start-up.

The impacts and benefits of tuning color and intensity in buildings will also eventually require the introduction of additional lighting quality dimensions to code. Similar to the outcome - based energy intensity approach, these lighting quality metrics will most likely have time-variant components and will therefore require some level of monitoring and/or self-reporting as well.

Acronyms and Abbreviations

AB	Assembly Bill
ANSI	American National Standards Institute
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CA	California
CCT	Correlated Color Temperature
CEC	California Energy Commission
CIE	International Commission on Illumination
CO_2	Carbon Dioxide
DALI	Digitally Addressable Lighting Interface
DLC	Design Lights Consortium
DOE	Department of Energy
DR	Demand Response
EISG	Energy Innovations Small Grant
EPIC	Electric Program Investment Charge
EUI	Energy Usage Intensity
GUI	Graphical User Interface
HDR	High Dynamic Range
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electro-Technical Commission
IECC	International Energy Conservation Code
IES	Illuminating Engineering Society
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISO	International Organization for Standardization
kWh	Kilowatt - Hour
LAP	Lighting Action Plan
LCD	Liquid Crystal Display

LED Light-Emitting Diode

LPD Lighting Power Density

M&V Measurement and Verification

NEMA National Electrical Manufacturers Association

NLCS Networked Lighting Controls Systems

OSI Open Systems Interconnection

PG&E Pacific Gas and Electric Company

RAD Readings at Desk

RGB Red, Green, and Blue

SBIR Small Business Innovation Research

SCE Southern California Edison

SDG&E San Diego Gas & Electric Company

SDO Standards Development Organization

SoC System on a Chip (integrated circuit)

TLED Tubular LED (linear replacement lamp)

VOC Volatile Organic Compound

GLOSSARY

API: Application programming interface, which is a set of communication protocols and tools for building software.

Demand Response: A mechanism through which an end-use's load profile is changed (by the user, a third party, or a utility) in response to system needs, often in return for economic compensation (e.g., payments or a different rate structure).

End Use: A service performed using energy (e.g., lighting, refrigeration) or a type of energy-using device (e.g., refrigerators, pool pumps). These end use and their demand for electricity make up customer load.

EPIC (Electric Program Investment Charge): The Electric Program Investment Charge, created by the California Public Utilities Commission in December 2011, supports investments in clean energy technologies that benefit electricity ratepayers of Pacific Gas and Electric Company, Southern California Edison Company, and San Diego Gas & Electric Company.

Internet of Things (IoT): The inter-networking of physical devices, vehicles (also referred to as "connected devices" and "smart devices"), buildings, and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to collect and exchange data over a network without requiring human-to-human or human-to-computer interaction.

Sector: A market or population segment sharing common characteristics. For the purposes of this study, the relevant sectors are: residential, commercial, and industrial (which includes agriculture).

Smart Grid: Smart grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.

Zigbee: An IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection. Hence, Zigbee is a low-power, low data rate, and close proximity (i.e., personal area) wireless ad hoc network.

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APPENDIX I: Permamote Light Sensor Testing

Summary

The Mote illuminance sensors were found to be proportionally responsive to light intensity, in agreement with the reference illuminance measurements. Dynamic range was found to be at from zero to over 4000 lux, well over the 2500 lux specification. However, the sensitivity of the Mote sensors appears to be low, and may require some adjustment to sensitivity settings or post processing.

For light levels below 1000 lux as measured by the reference sensor, the Mote sensors' illuminance measurements were found to be 0.792 to 0.795 X actual illuminance as measured by the reference sensor. At lower light levels the Mote sensors more closely matched reference measurements and at higher light levels the Mote sensors were found to deviate further.

Color temperature (CCT, Kelvin) and spectral data were measured by the reference sensor as well. The Mote sensors measured Red, Green, and Blue counts (analog), which will be post-processed to CCT for comparison with measured CCT results (this step has not yet been completed).

Objectives

This test report summarizes the results from lab testing carried out to verify and characterize the Mote sensor's ability to measure visible light intensity (in lux) as well as color parameters (R,G, B counts) that can be converted to color temperature (in degrees Kelvin).

Two Mote's lighting measurement performance was evaluated under several light sources and different conditions:

Electric Light Source Tests

- LED dimmable fixture retrofit engine, at four output settings
- Fluorescent dimmable desk lamp at two output setting settings
- Fluorescent 2'x4' dimmable T5 fixture, at four output settings

Daylight Tests

Daylight through windows in a model office environment (no electric lighting) with blinds fully open, and with light attenuated by lowered blinds at two slat angles.

Performance was characterized against reference lighting intensity and color temperature measurements from a lab grade spectral illuminance meter, with a second photosensor serving as a check against the reference meter. For details regarding instruments used for measurements, measurement parameter definitions, and test procedures, see *Mote Testing Protocol - Lighting.*

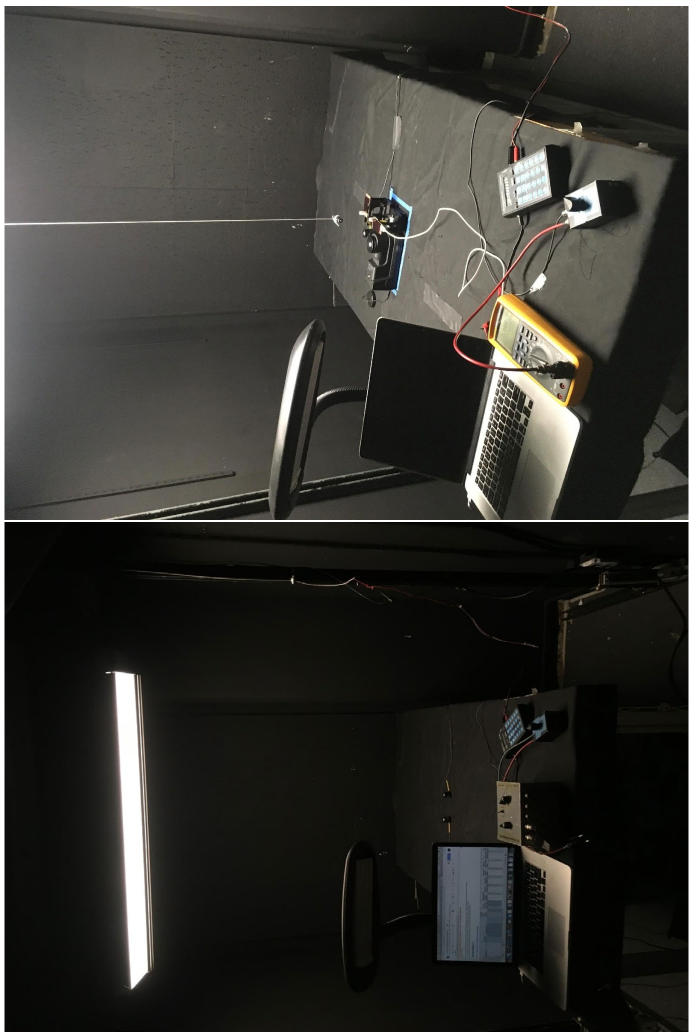
A table of data collected during the test procedures is presented in the Results section below. A brief testing report including those outcomes will be prepared after the tests are complete, to discuss the Mote's light sensing performance based on results from testing.

Test Setup and Execution

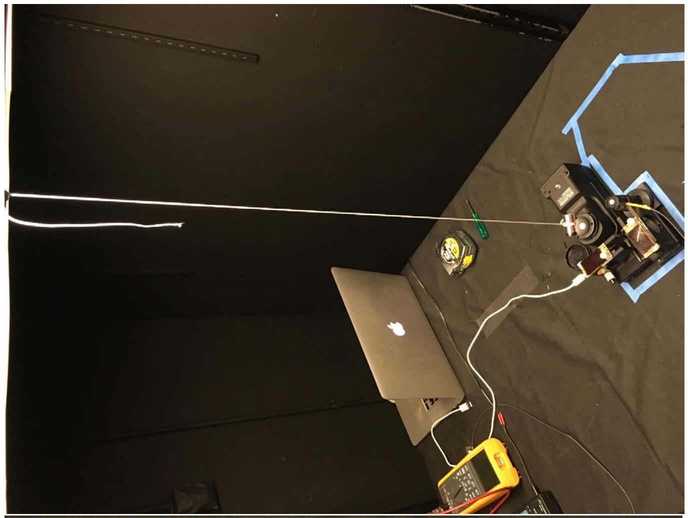
Electric light source tests

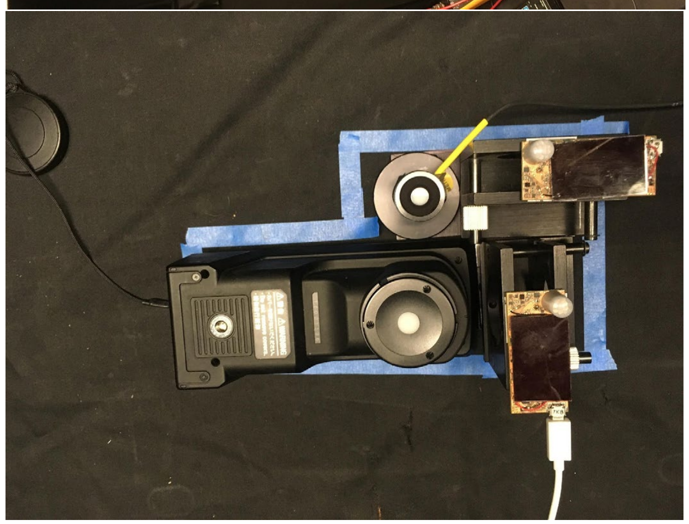
LED

LED dimmable light source (CREE dimmable light engine model #CR24-31L - 40K - 10V) hung on strut 42" above test bench; facing downward.



Mote sensors, CL500A, and LI 210-R, placed side by side, facing directly up, normal to light source, on test bench surface. Sensor faces 3" above bench, 39" from light source, centered latitudinally and longitudinally with respect to light source.



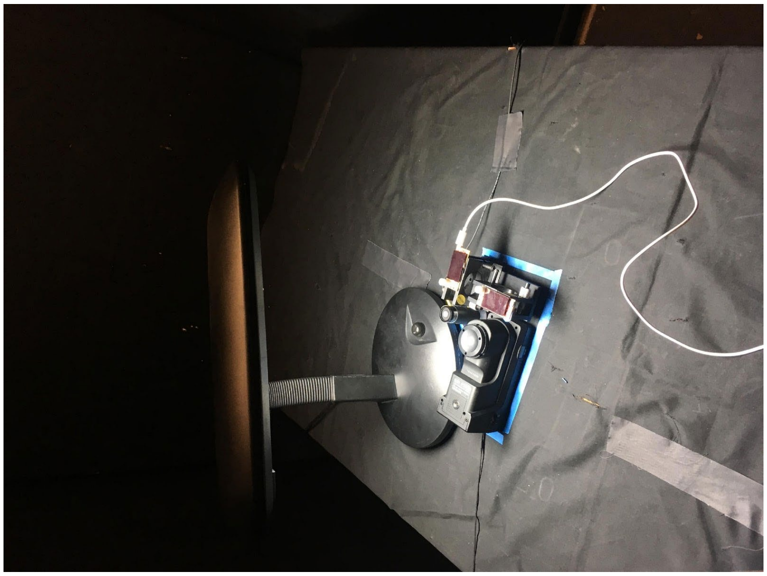


Light source turned on, and set to full output (10V DC dimming signal) and allowed to stabilize for 30 min. before first measurement. Three more readings taken at 6, 4, and 2V dimming signal with 10 min. stabilization between measurements.
Angle of incidence: Measurement at angle of incidence θ of 0°.

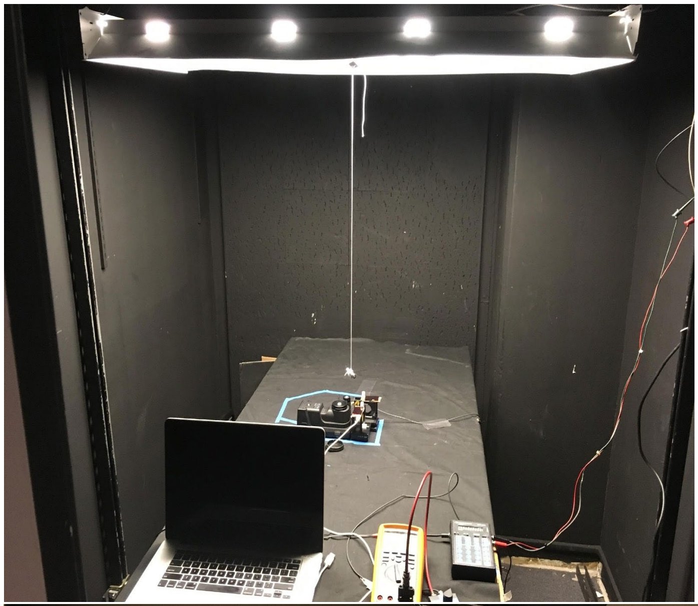
Date of tests: May 9, 2018.

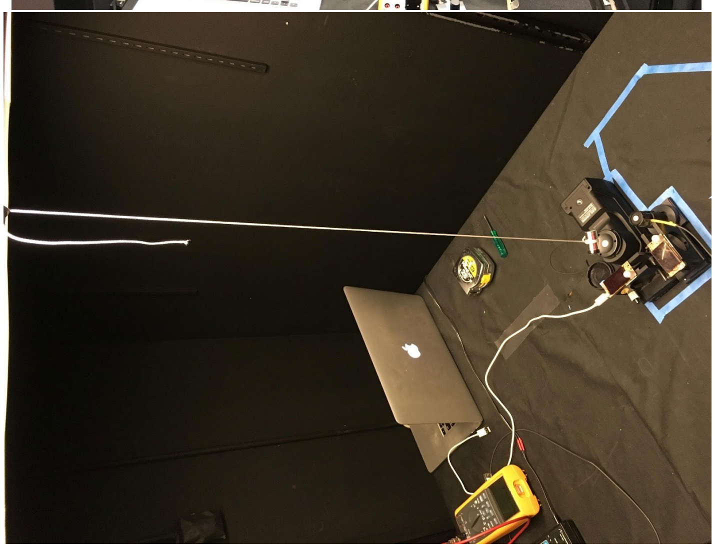
Fluorescent

Fluorescent dimmable desk lamp light source (Ultralux 55W 5500 Kelvin) placed adjacent to sensors, facing down, with light source 14” above test bench.



Fluorescent 2’x4’ 2-lamp T5 troffer hung 36” above test bench, facing down, 36” above test bench.





Mote sensors, CL500A, and LI 210-R, placed side by side, facing directly up, normal to light source, on test bench surface. Sensor faces 3” above bench,11” from desk lamp light source, and 33” from light source, centered latitudinally and longitudinally with respect to light source.

For desk lamp, light source turned on, and set to full output (via on-board dial) and allowed to stabilize for 30 min. before first measurement. Lamp then set to minimum output (via on-board dial) and allowed to stabilize before measurement.

For 2X4 fixture, light source turned on, and set to full output (8V DC dimming signal) and allowed to stabilize for 30 min. before first measurement. Three more readings taken at 5V, 2.5V, and 1V dimming signal with 10 min. stabilization between measurements.

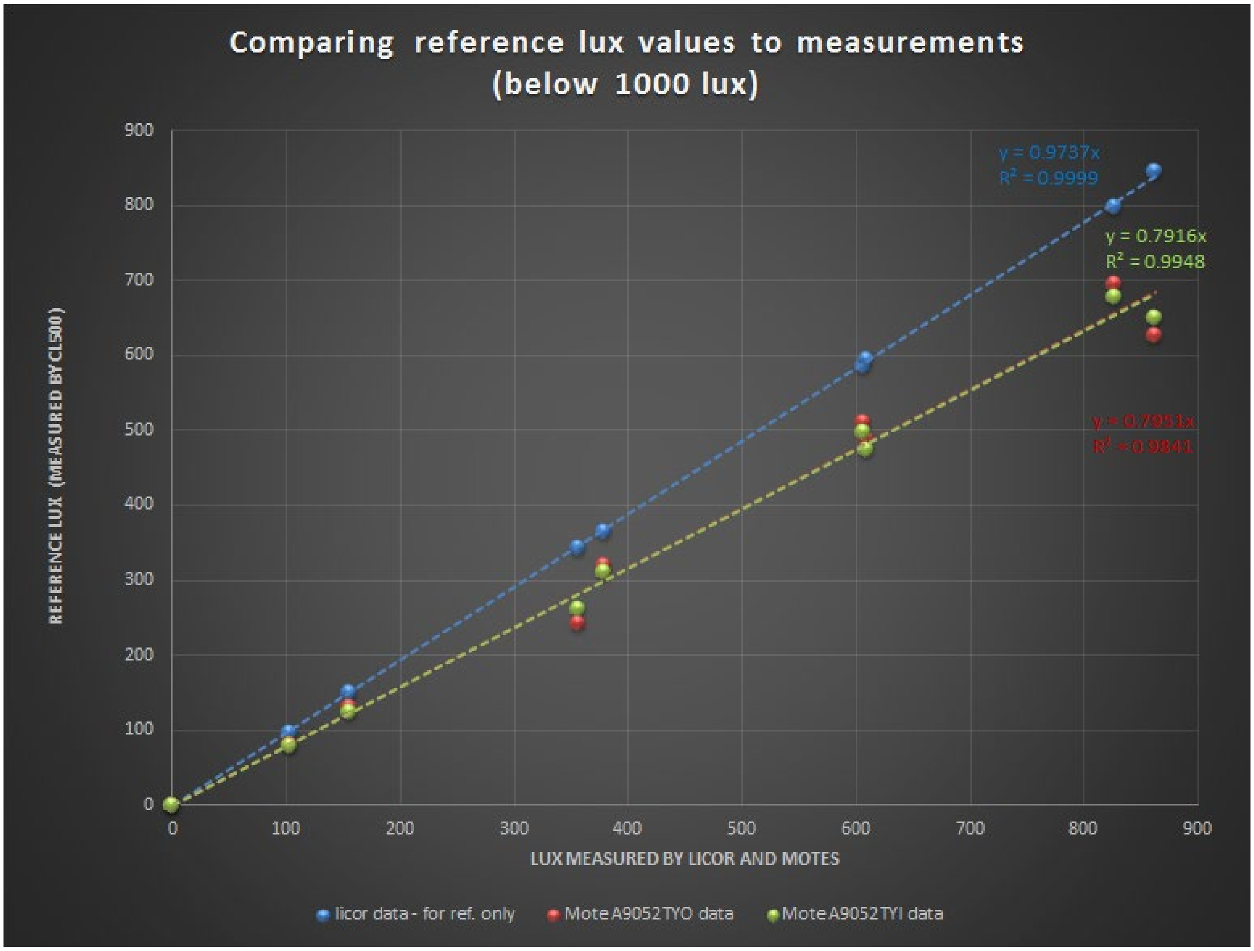
Angle of incidence: Measurement at angle of incidence of 0^{o}.

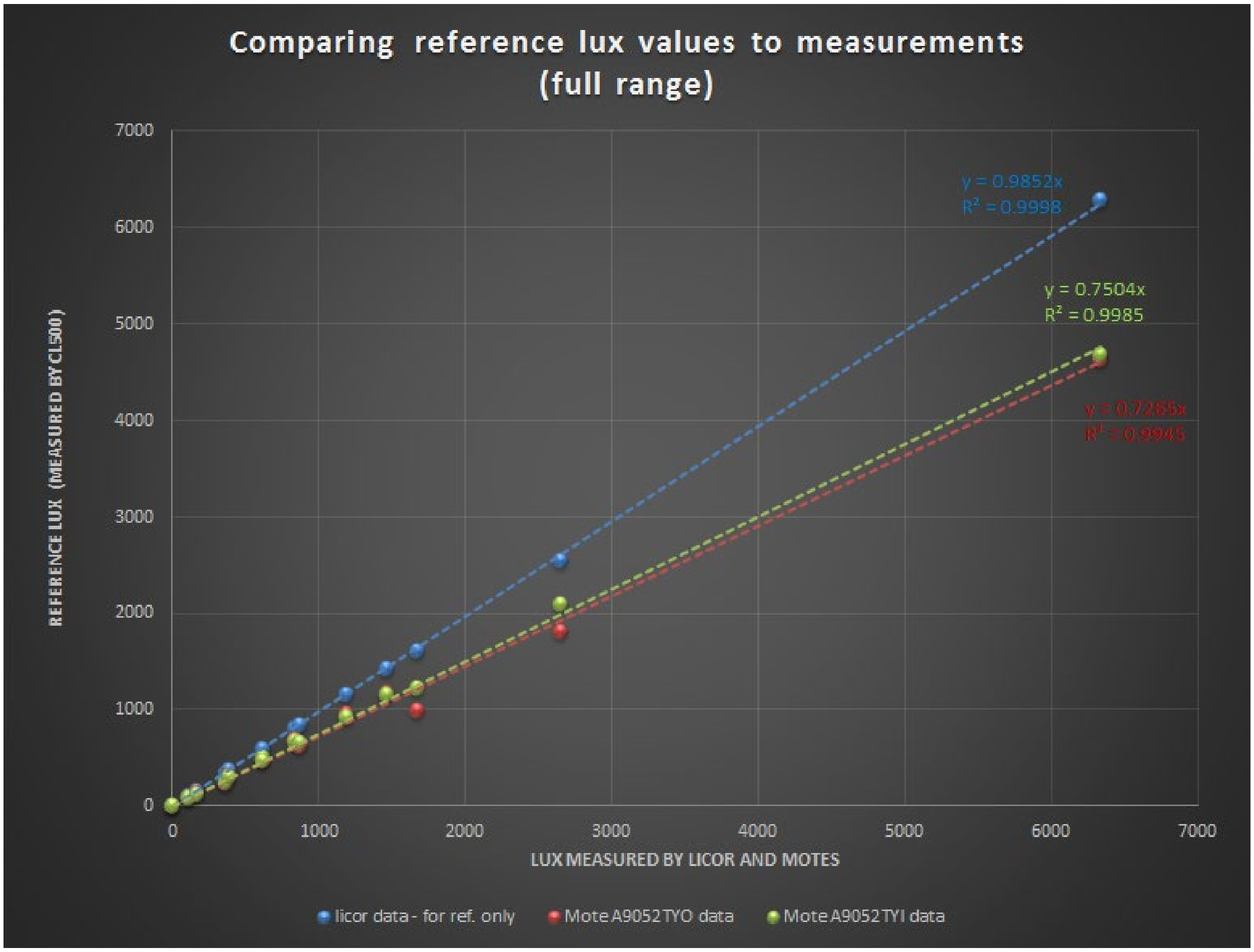
Date of tests: May 9 - 10, 2018.

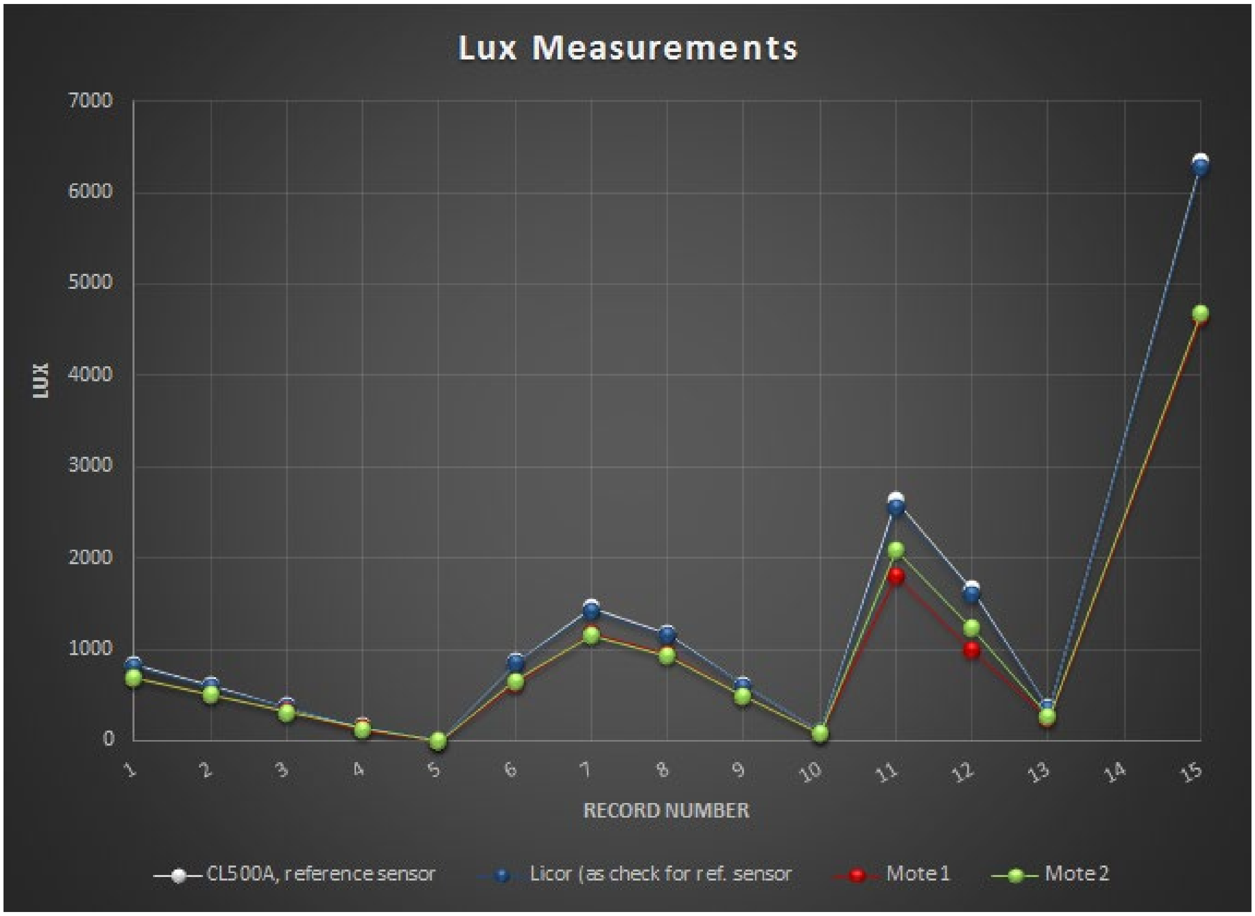
Daylight tests

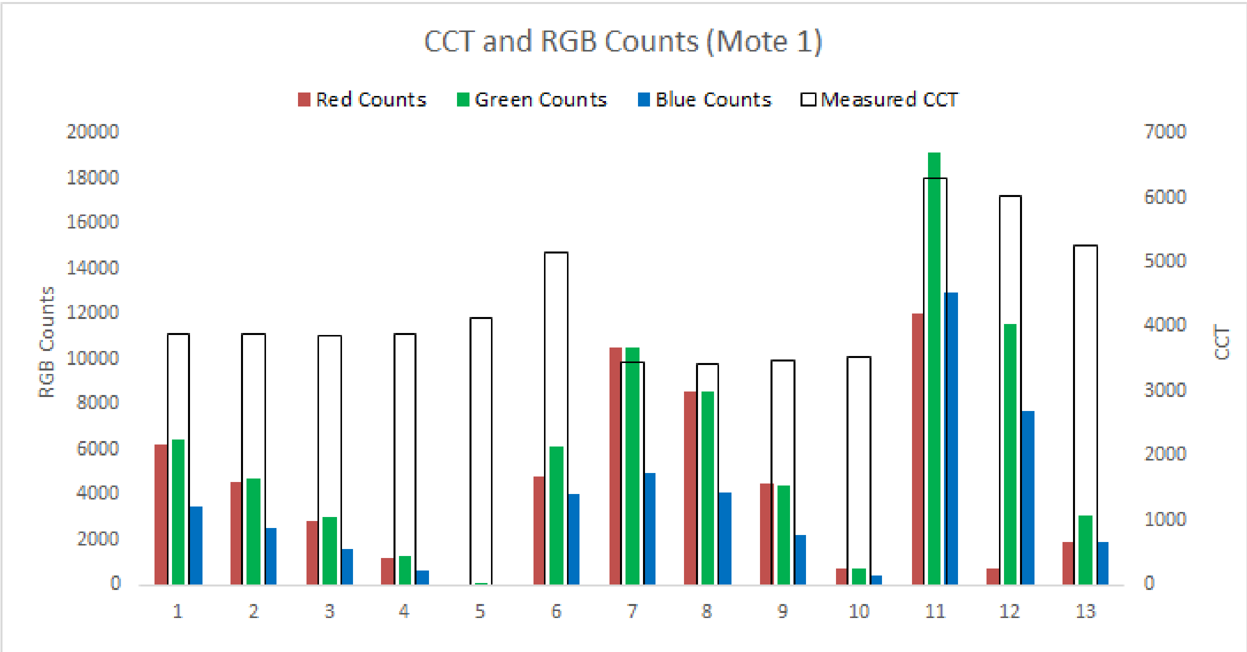
In a model office environment (FLEXLAB cell 1B) with furniture and typical ceiling, floor, and wall reflectances, the Mote sensors, and CL500 and licor sensors were placed on a desk surface (sensor surface 34" above floor), 8' from the window wall. Measurements of daylight only (electric lights OFF) were taken with blinds up and with blinds down and slats open (neutral angle) and fully closed.

Results


Comparing reference lux values to measurements (below 1000 lux)
REFERENCE LUX (MEASURED BY CL500)
LUX MEASURED BY LICOR AND MOTES
y = 0.9737x
R² = 0.9999
y = 0.7916x
R² = 0.9948
y = 0.7951x
R² = 0.9841
licor data - for ref. only
Mote A9052TYO data
Mote A9052TYI data


Comparing reference lux values to measurements
(full range)
REFERENCE LUX (MEASURED BY CL500)
LUX MEASURED BY LICOR AND MOTES
0
1000
2000
3000
4000
5000
6000
7000
y = 0.9852x
R² = 0.9998
y = 0.7504x
R² = 0.9985
y = 0.7265x
R² = 0.9945
licor data - for ref. only
Mote A9052TYO data
Mote A9052TYI data


Lux Measurements
7000
6000
5000
4000
3000
2000
1000
0
LUX
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
RECORD NUMBER
CL500A, reference sensor
Licor (as check for ref. sensor
Mote 1
Mote 2


CCT and RGB Counts (Mote 1)
Red Counts
Green Counts
Blue Counts
Measured CCT
RGB Counts
CCT
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
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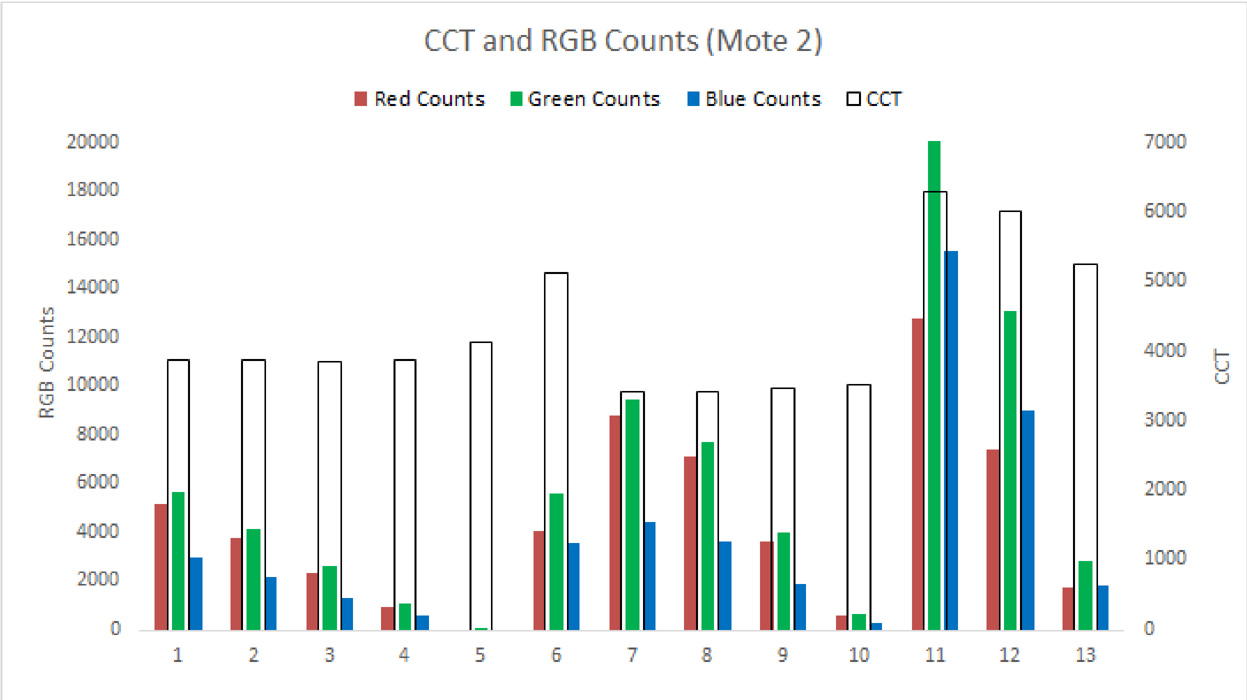
8
9
10
11
12
13


CCT and RGB Counts (Mote 2)
Red Counts
Green Counts
Blue Counts
CCT
RGB Counts
CCT
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
7000
6000
5000
4000
3000
2000
1000
0
1
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6
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9
10
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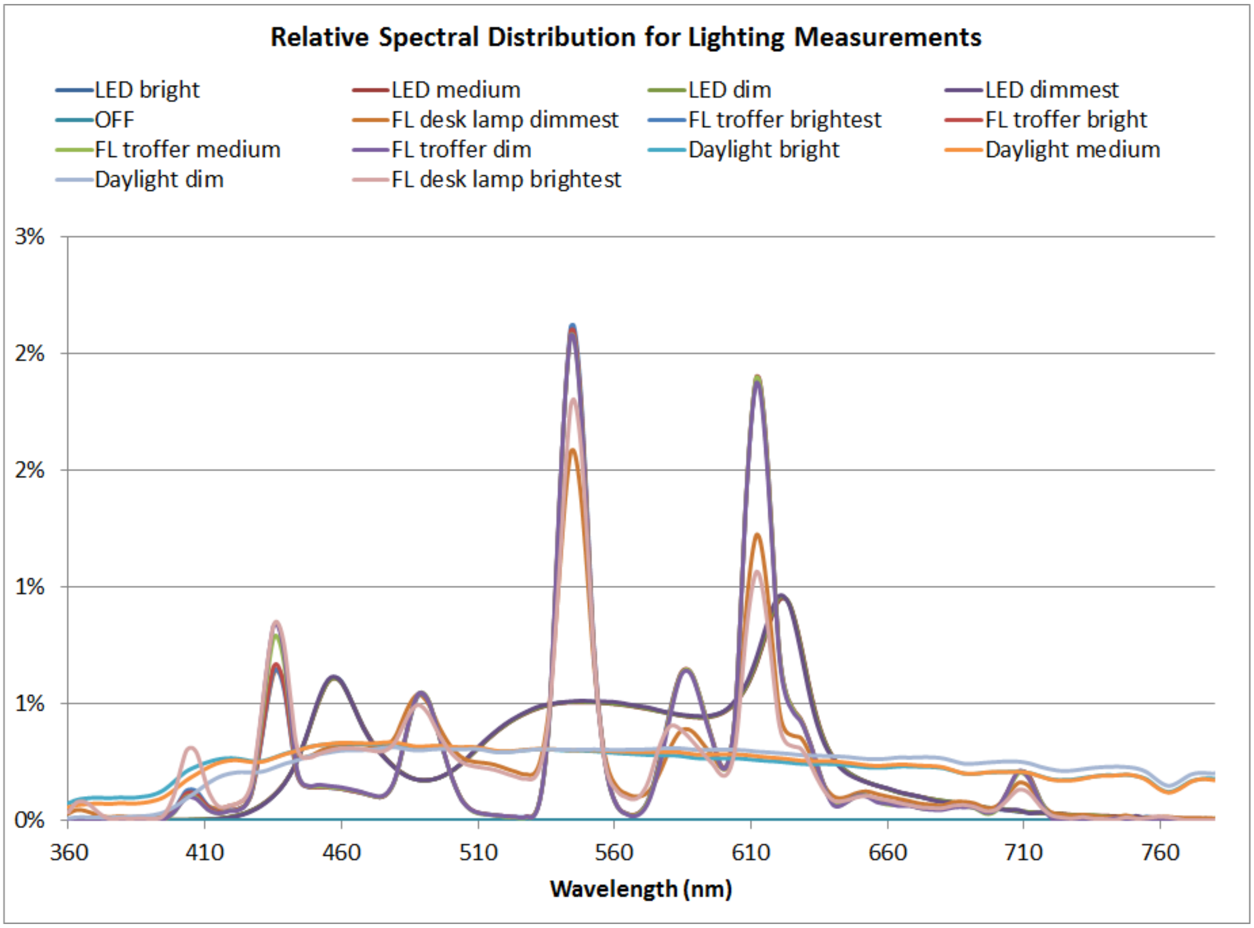
12
13



Relative Spectral Distribution for Lighting Measurements
LED bright
LED medium
LED dim
LED dimmest
OFF
FL desk lamp dimmest
FL troffer brightest
FL troffer bright
FL troffer medium
FL troffer dim
Daylight bright
Daylight medium
Daylight dim
FL desk lamp brightest
3%
2%
2%
1%
1%
0%
360
410
460
510
560
610
660
710
760
Wavelength (nm)

Date	Condition	Time	Record #	Control Setting	Lux CL500	Licor mV resist. of 24.91 koh	Lux Licor	Lux Mote 1 (A9052TYO)	Mote Lux / Reference Lux 1 (A9052TYO)	Lux Mote 2 (A9052TYI)	Mote Lux / Reference Lux 2 (A9052TYI)	CCT CL500	R counts Mote 1	R counts Mote 2	G counts Mote 1	G counts Mote 2	B counts Mote 1	B counts Mote 2
9-May	LED bright. θ of 0^{o}	2:40 PM	1	10V	826	6	800	697	0.844	680	0.823	3884	6204	5182	6425	5678	3450	2966
	LED medium. θ of 0	2:50 PM	2	6V	606	5	587	513	0.845	498	0.822	3879	4585	3820	4700	4182	2526	2182
	LED dim. θ of 0	3:00 PM	3	4V	379	3	367	320	0.844	312	0.825	3872	2816	2371	2965	2640	1587	1349
	LED dimmest θ of 0	3:10 PM	4	2V	155	1	150	132	0.852	125	0.810	3877	1149	964	1235	1073	651	558
	OFF	3:15 PM	5	OFF	0	0	1	0	0.000	0	0.000	4134	0	0	2	2	0	0
	FL desk lamp dimmest θ of 0o	4:00 PM	6	knob turned to dimmest setting	862	7	846	628	0.728	651	0.755	5144	4770	4091	6094	5638	3994	3605
10-May	FL troffer brightest θ of 0o	11:40 AM	7	8V	1460	11	1419	1175	0.805	1152	0.789	3438	10529	8808	10506	9492	4974	4416
	FL troffer bright θ of 0o	12:00 PM	8	5V	1181	9	1151	950	0.805	927	0.785	3435	8579	7169	8530	7700	4082	3615
	FL troffer medium θ of 0o	12:10 PM	9	2.5V	609	5	595	490	0.804	475	0.780	3472	4446	3679	4422	4032	2205	1917
	FL troffer dim θ of 0o	12:20 PM	10	1V	102	1	98	83	0.813	81	0.795	3530	735	610	746	680	380	328
	Daylight bright	12:50 PM	11	blinds up	2639	20	2552	1809	0.685	2085	0.790	6313	11984	12844	19192	22116	12932	15599
	Daylight medium	1:00 PM	12	blinds down slats neutral	1668	13	1606	996	0.597	1227	0.736	6025	699	7441	11531	13074	7711	9004
	Daylight dim	1:10 PM	13	blinds down slats closed	355	3	345	243	0.685	264	0.741	5262	1908	1736	3032	2818	1902	1821
9-May	FL desk lamp brightest θ of 0	3:45 PM	15	knob turned to brightest setting	6331	50	6279	4631	0.731	4677	0.739	5616	33603	28325	46286	41834	30498	26479

APPENDIX II: Permamote Occupancy Sensor Testing

Summary

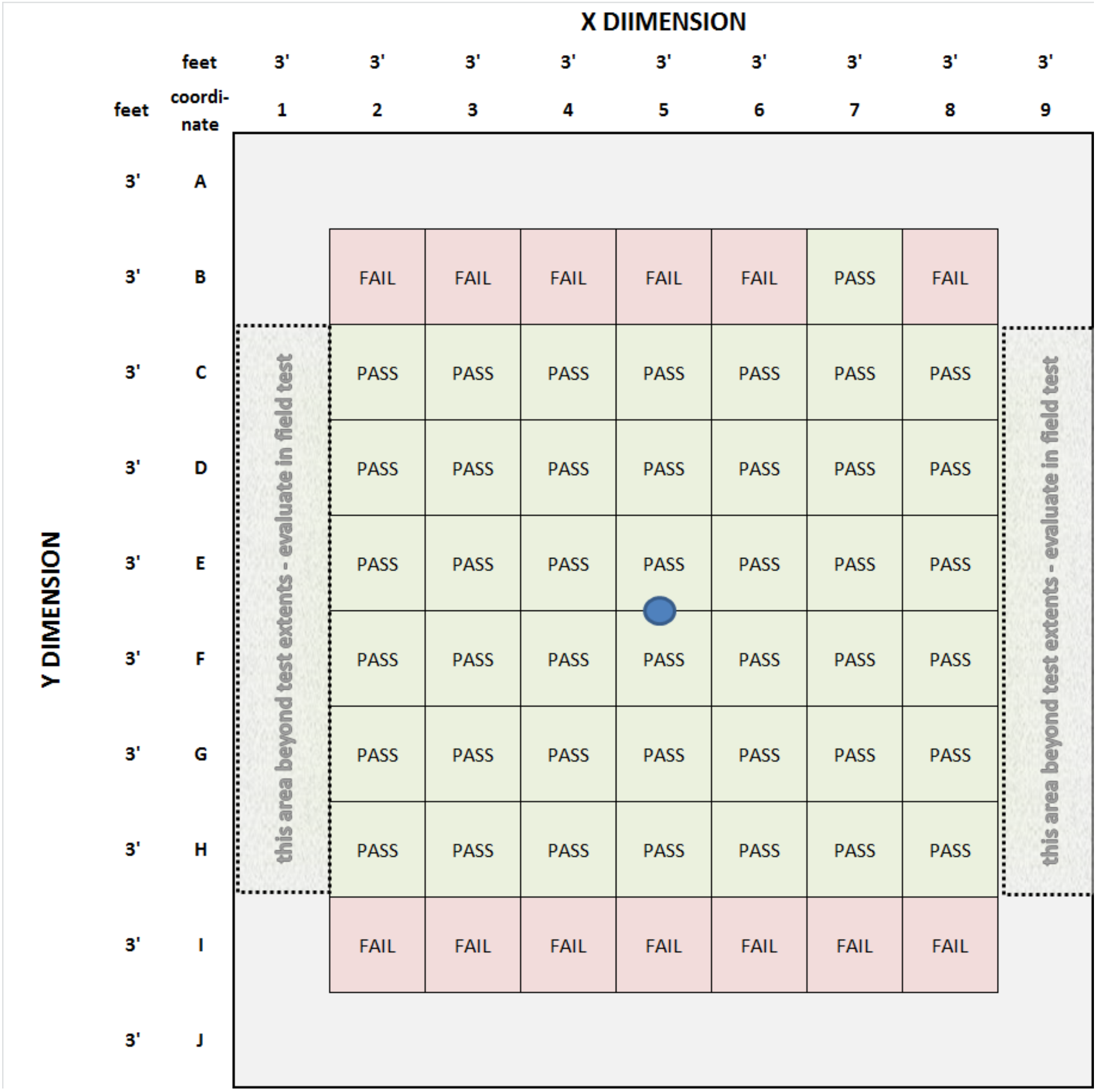
The Mote occupancy sensor was found to be responsive to motion, within expected sensitivity based on manufacturer specification on field of view for the sensor at the mounting height tested (9’ 4”). For major motions (subject movement between 3’ by 3’ cells under sensor), the detection area was around 21' x 18', close to our sensor specification of 20'x 20' (albeit that specification was for 8’ mounting height). For minor motions (smaller motions within the 3’ by 3’ cell) the field of view was found to be around a 6’ radius from sensor center, better than the sensor specification requirement of 5'x 5' detection area.

Summarized below are results from the PIR testing, carried out according to the NEMA standard for motion sensor testing, within the constraints of the test environment. The sensor was mounted on an acoustic drop ceiling in an office environment centered over a 3’ by 3’ grid of test cells marked on the office floor.

Results

Major Motion

For major motion detection, the subject crosses into each test cell boundary either latitudinally or longitudinally. The sensor field of view (FOV) for major motion at 9'4" mounting height was found to be at least 21' x 18'; 378 square feet, within the FOV calculated from Panasonic's published detection parameters for the sensor.



Minor Motion

Minor motions are defined as 15" arm at 36" height rotating 90 degrees through the x-y plane (horizontal) or the x-z plane (vertical). Testing criteria passes allows 1 detection for up to 4 movements through either plane for a pass. For the minor motion tests, the subject sat centered in each test cell, with arm at the defined height, and rotated it through the defined planes up to 4 times and if motion was detected this was recorded as a Pass.

Based on results from the tests, the sensor FOV for minor motion is best described by a 6' radius around the center of the sensor mounting location for a detection area of around 113 square feet, though minor motions testing in 3' square cell resolution was found to be a bit coarse for tests at FOV limits. Some cells in the extremes only detected minor motions on the cell side closest to the sensor.

X DIIMENSION

Y DIMENSION

	feet	3'	3'	3'	3'	3'	3'	3'	3'	3'
feet	**coordi-nate**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3'	A									
3'	B		fail	fail	fail	fail	fail	fail	fail	
3'	C		fail	fail	fail	fail	fail	fail	fail	
3'	D		fail	fail	pass	pass	pass	fail	fail	
3'	E		fail	pass/fail	pass	pass	pass	pass/fail	fail	
3'	F		fail	pass/fail	Pass	pass	pass	pass/fail	fail	
3'	G		fail	fail	pass	pass	pass	fail	fail	
3'	H		fail	fail	fail	fail	fail	fail	fail	
3'	I		fail	fail	fail	fail	fail	fail	fail	
3'	J									

Latency

Twelve measurements of the latency of motion detection were taken during Major Motion tests. Latency here is defined as the time between subject motion and sensor-reported motion. Latency was found to be well within the sensor specification of less than one second between motion and motion detection.

Subject motion was time-stamped by hand-held "click" via wireless device (USB-port connected) during Major Motion test, converted to time-stamp from laptop clock by python script. The time stamp of PIR sensor-reported motion was determined by connecting the sensor to the same laptop via USB and pulling time-stamp for detected motion from the laptop clock with python script.

- RECORDS: 12
- AVERAGE LATENCY: 307 mSec
- MINIMUM LATENCY: 13 mSec
- MAXIMUM LATENCY: 963 mSec

Note that latency as measured in these tests is different than the end-to-end latency between motion and action induced by sensor response and control system response, which will include time from PIR sensor response to control system action. This may be tested later in field demonstrations when and if sensor is integrated into control system.

Test protocol

The occupancy sensor test protocol defined the lab testing to be carried out to characterize the Mote sensor's ability to detect motion for occupancy purposes. The Sensor Specification Memo for the Mote design laid out the following performance targets for occupancy sensing:

- Detection area at 8 feet: 5'x 5' to 20'x 20'
- Sense small movement within 2 inch in diameter
- Sense large movement at a speed >= 1m/s
- False positive rate < 0.1 per hour
- Latency of detection (90% detection probability): <1s

The Mote's performance was characterized according to principles laid out in the NEMA WD 7-2011 (R2016) Occupancy Motion Sensors Standard protocol:

> Scope
>
> *This standard publication covers the definition and measurement of field of view and coverage characteristics relevant to the use and application of vacancy and occupancy sensors using individual or any combination of passive infrared, ultrasonic, or microwave technology. These sensors are used in systems for control of lighting, heating, ventilating, and air conditioning (HVAC), and other devices.*

Test Setup Images


LOUISVILLE

APPENDIX III: Proposed Lighting Control User Interface Standard

Introduction

User interface standards enable efficient, effective, and correct communication between human beings and devices they utilize. User interface standards have a long history of success in areas such as vehicles and communication. This standard extends standard user interface principles to the control of light sources.

1.0 Overview

1.1 Scope

This standard defines user interface elements for manufacturers to use in the design of lighting controls. It is applicable to hardware controls, software displays, and documentation. The proposed standard was created foremost for controls experienced by people in their ordinary lives, at home, work, or elsewhere. However, it may also be used for professional controls that are only used in the course of a job function (e.g. large building central controls or theatrical controls) but may be applied to those. The controls may be dedicated lighting controls, controls for many purposes (e.g. home automation systems), or controls with some other specific primary function (e.g. shading/lighting coordination with HVAC for efficient thermal comfort).

The standard covers the following topic areas: Lighting in General, Basic Switching, Brightness, Dynamic Control, Color,, and Other Topics. The standard addresses visual elements (terms, symbols, and colors), dynamic elements (indication and actuation), audio elements (sounds and words), and tactile elements (identification and actuation).

The standard does not cover ergonomic or safety issues that might be associated with lighting controls.

1.2 Purpose

The purpose of this standard is to enable users of lighting controls to more easily understand what controls can do, their current state, and what users need to do to accomplish their goals.

2.0 References

This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

- CIE Technical Report CIE 107-1994, Review of the official recommendations of the CIE for the colours of signal lights, International Commission on Illumination.
- IEC 73:1996. Basic and safety principles for man-machine interface, marking and identification — Coding principles for indication devices and actuators. Geneva, Switzerland: International Electrotechnical Commission.
- IEC 447:1993, Man-machine interface (MMI) — Actuating principles.

- IEC 60073:2002, Basic and safety principles for man-machine interface, marking and identification—Coding principles for indication devices and actuators.
- IEC 60417-1:1998, Graphical symbols for use on equipment—Part 1: Overview and application.
- IEC 60417-2:1998, Graphical symbols for use on equipment—Part 2: Symbol originals.
- IEC 80416-1:2001, Basic principles for graphical symbols for use on equipment—Part 1: Creation of symbol originals.
- IEC 80416-3:2002. Basic principles for graphical symbols for use on equipment—Part 3: Guidelines for the application of graphical symbols.
- IEEE 1621, Standard for User Interface Elements in Power Control of Electronic Devices Employed in Office/Consumer Environments, 2004.
- ISO 7000:1989, Graphical symbols for use on equipment: Index and synopsis.
- ISO 9241-10:2001, Ergonomic requirements for office work with visual display terminals (VDTs)—Part 10: Dialogue principles.
- ISO 9241-1:1996, Ergonomic requirements for office work with visual display terminals (VDTs)—Part 1: General introduction.
- ISO/IEC 13251:2000, Collective Standard—Graphical symbols for office equipment.
- ANSI/VITA 40-2002, Service Indicators.
- SAE 2010. J2402_201001 - Road Vehicles - Symbols for Controls, Indicators, and Tell-Tales, 2010.

3.0 Definitions

lighting control: A device which can actively change the light output of a light source.
Note: A lighting control may be part of the same device as the light source but is usually a separate device.

lighting control: The combination of manual lighting control and automatic lighting control.

lighting control user interface: The part of a device with which a user interacts to receive information from a lighting control, and that the user uses to communicate commands and preferences to the control.

manual lighting control: An action taken by a user to change the light output of a light source.
Note: manual actions may also change automatic functioning of a lighting control.

automatic lighting control: An action taken by a lighting control to change the light output of a light source that is not the direct immediate result of manual action.
Note: manual actions may also change automatic functioning of a lighting control.

power state: A condition or mode of a light source that broadly characterizes its light output and power consumption. Basic power states are on and off.

secondary actuation: A method of using a control element that is in addition to the primary usage modality. An example is when a button “press” is different from “press-and-hold.”

user interface element: An individual written word, symbol, indicator, spatial relationship, audio word, or other item that cannot be usefully subdivided and is apparent to the user.

4.0 Lighting control user interface elements

Lighting control concepts should be categorized according to topic areas as follows:

- General Principles
- Lighting in General
- Basic Switching
- Brightness
- Dynamic Control
- Color
- Other Topics

4.1 General principles

This standard does not make requirements about when a particular user interface element should be included, but rather only specifies what should be used when an element is included. For example, it does not specify that on/off controls should be oriented vertically, but does specify that if such a control is vertical, then an upward actuation or indication should mean "on" and/or "more."

Basic use of a lighting control should be clear to a user who has not previously used the control but is familiar with the content of this standard. Limited experimentation may be needed, such as understanding the light sources to which a control applies. Basic use includes on/off switching, setting brightness levels, and understanding if sensors (e.g. occupancy or ambient light) are involved in control.

Lighting controls should have visual cues to indicate that they address lighting. This may be the presence of lighting-specific symbols, or visual appearance that is readily associated with common control types currently in buildings. The location of a lighting control may also be important to it being readily perceived as being a lighting control.

Lighting concepts and individual elements should not be specific to a particular interface type (e.g. mechanical, display-based, voice-based) or to a particular building type.

While this standard specifies individual interface elements, it does not require their use. For example, a simple on/off switch may use the mechanical position to indicate which position is on and which position is off, and so additional explanation via terms or symbols is not needed. Similarly, an element may be displayed only intermittently.

Control elements used that are not lighting-specific should be selected with consideration of appropriate international standards, particularly for symbols. Examples include Lock/unlock, Undo, etc.

All terms in user interfaces should be appropriately translated to the local language(s). The standard only references terms in English, and does not define translations. In general, symbols are preferred over terms to increase comprehension.

A secondary actuation is a way to use a control that is in addition to its basic usage, and likely not obvious to the casual user. Examples include pressing and holding a button (rather than immediate release), tapping several times in quick succession, or pressing in a rotary control before rotating it. Secondary actuations should be avoided unless there is a graphic indication of their existence and meaning, or if the secondary actuation is for a configuration or maintenance purpose only.

The content in this document applies to hardware and software produced by lighting control companies, as well as to software configuration and detailed decisions made at the time of product installation.

4.1.1 Physical mappings

Physical mappings of user actions should be used in accordance with IEC 447 as summarized in the following table. If a control uses a combination of two actions (e.g. two buttons arranged around a diagonal line) then both associations should be employed.

Associations for common actions.

Effect **Action**	**Increasing**	**Decreasing**
Vertical motion	Up	Down
Rotation	Clockwise	Counterclockwise
Horizontal motion	Right	Left
Motion (re: operator)	Away	Towards

To indicate controls for “more” or “less” (e.g. of light level), the symbols plus + (5005), and minus — (5006) may be used. Alternatively, equilateral triangle symbols pointing up or to the right for more, or down or to the left for less may be used.

4.1.2 Speech Interfaces

Use the terms “Turn on,” “Turn off,” “Dim,” and “Brighten.” Enable light levels to be set by a command of “Set” and use percentages for levels of maximum brightness.

4.1.3 Indicators and other Feedback

A light control may include a “locator light,” a small light source on a control, which only has the function to help the user find the control when the room or space is dark. Locator lights should be white unless there is a specific reason to be a different color, but in no cases should the locator light be red. Indicators in general should follow IEC 73, which means that red should only be used to indicate an error, warning, or emergency. In cases where a distinction is being made among red, green, and/or yellow, the indicator should follow the color restrictions of standards for traffic signal lights (CIE 107).

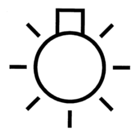
Locator lights should be constant (not blinking) but can optionally be off when the light being controlled is on. Indicators should only flash when there is a dynamic condition underway (e.g. the lighting control is in a temporary transition state) or the control is trying to attract the attention of the user. That is, indicators should be static unless there is a specific reason for them to be dynamic.

The “locator light” should be located so as to not be confused with a status indicator. It may be turned down or off when the light source is active, or left unchanged. In documentation the term “locator light” (or a variant) should be used.

Audio (other than voice) and haptic signals may be used to augment controls, but reliance on these should be avoided.

4.2 Lighting in General

Controls should use the IEC standard symbol for lighting to refer to the overall concept of lighting. An example is to this symbol to alert a user to the lighting controls section of an application or management system that includes other uses.



IEC symbol 5012: Lamp; lighting; illumination

4.3 Basic Switching

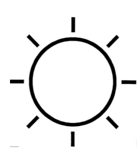
To switch a light source on or off, controls may use any physical arrangement of control elements as long as they follow prescriptions in ISO 447 for physical mappings as described in Section 4.1. These include that “on” or “more” is associated with up, to the right, clockwise, and away. Controls may use the IEC symbols for On I (5007) and Off O (5008), the Power symbol ⏻ (5009), or words that are the basic translation of these into the local language. Symbols are preferred. Basic switching controls the “power state” of the light. “On” and “Off” assign the state; “Power” toggles between the two states. A control that also includes the ability to change the light level to intermediate states may return to an intermediate level after an off-on cycle.

For applications in which the On I and Off O symbols alone or as a pair may be unclear to the user, the Power symbol ⏻, is recommended.

A light level may transition over a period of time that is noticeable to the user, but less than 10 seconds. This type of “ramp” or “fade” has no specified interface elements.

4.4 Brightness

User preferences about adjusting luminance levels should be organized around the concept of Brightness, and indicated graphically with the IEC standard symbol for Brightness.

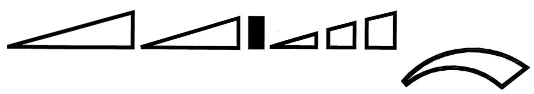


IEC symbol 5056: Brightness

Brightness levels should map onto a numeric scale, implicitly or explicitly. This standard does not specify what numeric value should correspond to the maximum brightness of a source, but a zero value should correspond to no light output. Brightness may be used to refer to the light output from one or more sources, or to a desired light level at a location which includes light contribution from natural or other artificial sources.

Brightness values should map onto a linear scale for how the user experiences light levels. Note that this may combine the scale produced by a lighting control device with how brightness levels are used by the light source.

The concept of Dimming may be used but should be limited to changes in Brightness levels. No symbol for dimming is defined, but any standard symbol for variable control may be used (the following Figure shows four of these).



IEC symbols (last is ISO) **for Variability: 5004, 5183, 5181, 1364**

As with switching, mechanical associations with brightness levels should follow those specified in ISO 73 / IEC 447, and use of symbols should be as described in Section 4.1.1.

Control for power state and for brightness may be combined.

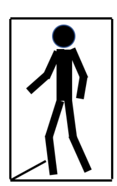
4.5 Dynamic Control

Dynamic control includes control based on human occupancy, daylight (ambient light), and time-based control.

4.5.1 Occupancy Control

Light controls that modulate light levels in response to information about human presence in the illuminated space should use the concept of Occupancy. This may include devices that sense occupancy, or controls that act on that information

To indicate Occupancy, controls shall use the symbol shown below. This is not an existing ISO/IEC standard symbol, as no such symbol currently exists.



Occupancy Symbol

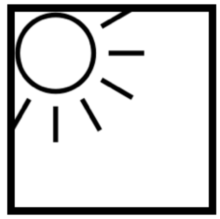
Vacancy control is a form of occupancy control.

4.5.2 Daylight Control

Light controls that adjust artificial light levels in response to ambient light (principally from daylight) should use the concept of Daylight. This may include devices that sense ambient light, or controls that act on that information.

Should either the term "Sunlight" or "Ambient Light" be used instead of Daylight?

To indicate Daylight, controls shall use the symbol shown below. This is not an existing ISO/IEC standard symbol, as no such symbol currently exists.



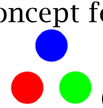
Daylight Symbol

4.5.2 Time-based Control

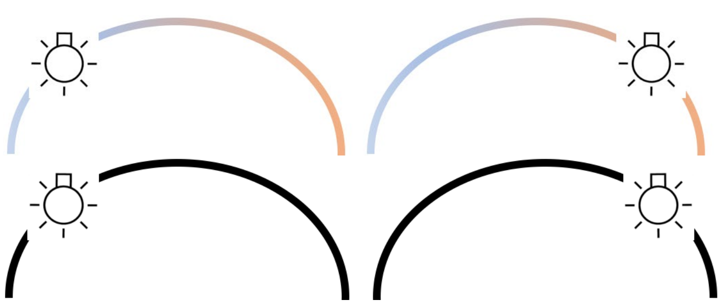
To indicate a time-based schedule, the Date symbol 

(5662) or the Clock/Time symbol  (5184) should be used.

4.6 Color

To indicate the overall concept for light color, lighting controls that modulate color should use the IEC symbol for Color  (5048). No further concepts or symbols are specified for setting or changing colors.

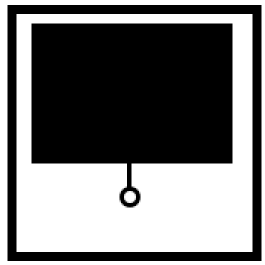
For color temperature of white light, the overall concept to use is time-of-day, with "cooler" white colors associated with the morning, and "warmer" white colors associated with the afternoon or evening. There is no international standard symbol for morning or afternoon so the symbols to use for cool and warm light are proposed as shown below. The arc shows the path of the sun across the sky, with the sun replaced by a lighting symbol.



Symbols for "Morning White" and "Afternoon White".

4.7 Other Topics

Controls for shades should be organized around the concept of Shading. The baseline is no shade, so that more shading is less light into the room from the outside. This applies regardless of the technology used for shading. The concepts of ‘on’ and ‘off’ are not required to be applied to shading, but if they are, then ‘on’ corresponds to maximum shading.



Symbol for window shading.

APPENDIX IV: Background and Development of Lighting Control User Interface Standard

1.0 Overview

This appendix provides background information for the choices made in creating content for this standard.

> *Outstanding questions are included for the reader's consideration, both indented and italicized.*

1.1 Scope

The intent of this standard is to cover a modest scope that is clearly needed and/or where a good choice of concepts, topics and other content seems clear. After a few years, we anticipate that the standard will be revised and extended, informed by experience from designers and users, as well as input from individuals and companies outside the U.S.

While the scope covers tactile elements, the standard content currently does not include any tactile elements.

1.2 Background

This proposed standard takes inspiration from a variety of sources. Basic foundational controls are specified in a number of ISO and IEC standards for symbols, indicators, and physical mappings. An example successful standard is SAE J2402 which covers a wide variety of content and is used throughout the world in many vehicle types, and has been extended as technology used in vehicles has evolved. A user interface standard which more deeply coordinates works, symbols, colors, and metaphors is IEEE 1621. IEEE 1621 covers the user interface for power control of electronic devices (entire products) that people commonly interact with in their home and work life. IEEE 1621 was finalized in 2004 and is recommended by the ENERGY STAR program for many electronic products. IEEE 1621 covers user interface elements for how devices convey their power state to a user, and how a user changes the power state, which is structurally similar to the lighting control topic. Background material on IEEE 1621 can be found at [Nordman et al., 2002].

Background research for this standard on lighting control was created as part of two projects. Results can be found in [Nordman et al., 2011] and [Nordman et al., 2017].

This research mostly covered products currently available in the United States; most products assessed were from companies that participate in the lighting controls activities of the National Electrical Manufacturers Association (NEMA).

2.0 References

Lighting controls should use content and principles from well-established International standards as listed in section 2.0 of the standard unless compelling reasons exist to deviate. Most of the content of these standards is quality material to bring to lighting controls. Using other standards as a basis increases the degree to which lighting controls will be compatible with other user interfaces. Lighting controls frequently are part of a larger control system; vehicle dashboard controls are an example of this, as are emerging residential-scale building control technologies.

CIE Technical Report CIE 107-1994 includes specification of specific colors of indicator lights for traffic signal lights to ensure that they are accessible to people who are color blind.

Note that the references shown may not be the most current versions. We have not yet confirmed whether the current versions have changed in ways that may affect this standard.

3.0 Definitions

The definitions listed here are primarily to help organize the ideas in the standard. "Power State" is adapted from the definition in IEEE 1621.

"Lighting control" could refer to the *physical device* which originates control (through direct manipulation of power flow or through sending information), the *use of* that device, or to the *effect of* using the device on light output. The International Lighting Vocabulary [CIE, 2017] defines "17-688: local control: operation of a sign or a luminaire from within the device or in its proximity by means other than by manual operation." This appears to match what we define as automatic control, since it is differentiated from manual (although "local" seems ambiguous).

4.0 Lighting control user interface elements

4.1 General principles

Lighting controls have historically been limited in the number of explicit clues they offer such as words or symbols to label switches or dials. This is understandable given the prominence they generally have in rooms, their familiarity, and their historic simplicity. Future lighting controls are unlikely to resemble miniature versions of vehicle dashboards in which every control is explicitly labeled. That said, the number of control modalities that commonly exist and the portion of controls that have many modalities will increase, so it is likely that significantly more user interface content will be used in future. The standard provides guidance on what content to use.

Standard symbols are references for what a user is expected to have in mind for a concept. A manufacturer may deviate from the reference, but should do so in a way that is readily connectable to the original symbol/concept so that meaning is not lost.

Visual elements specified by this standard may be omitted when meaning remains clear. For example, mechanical switch position can imply "on" vs. "off" without needing written words or symbols, and controls only for lights (for example, common wall switches) usually do not require a symbol for lighting in general. For other examples, an indicator light may indicate status of an on/off or brightness control.

Secondary actuation mechanisms are typically not obvious to the user without some user instruction and so are confusing if presented without clear visual cues of their existence and associated action. Secondary actuation mechanisms for configuration and maintenance will generally not be employed by ordinary users, and so these functions can be treated differently.

Should indication of secondary actuation methods be required or recommended?

For symbol standards, a useful tool to find and evaluate international standard symbols is the Online Browsing Platform (OBP) - https://www.iso.org/obp/ui/#search. This covers the core ISO and IEC symbol standards as well as others such as for safety markings. The International Lighting Vocabulary (ILV) is available at: http://eilv.cie.co.at/, though very few terms in the ILV apply to controls.

4.1.1 Physical Mappings

The symbols for plus + (5005), and minus — (5006) were created for and are defined about electrical polarity (e.g. on a battery). Despite this, when used to increase or decrease a value (e.g. brightness) the symbols seem to have clear meaning, particularly when used as a pair.

International symbol standards lack a pair of symbols with a triangles pointing up and down. These are commonly used on lighting controls and are also clear; they should be adopted as international symbols. There is a triangle pointing up (Bleach - for laundry), and pointing down (Monophonic - for audio), but these are not commonly used. Triangles are used as a shape in signage to indicate warnings (e.g. yield signs in traffic control), but this is not likely to be confused with the use of a triangle pointing up to mean ‘more’ in the lighting control context, particularly when paired with a triangle pointing down.

Note that the physical mappings of Table 1 of the standard reflect the mappings of the action of the user, not the resulting state of the control. For example, a paddle switch pressed in at the top for “on” will then protrude from the bottom; the *action* corresponds to up/more, not the resulting position.

4.1.2 Speech Interfaces

Speech interfaces (voice) are relatively new and rapidly evolving. We suggest caution to see how these evolve, but also urgency because needed standards should be created quickly before non-compliant usages become common.

Inevitably for lights speech interfaces require sentences of commands to perform an action that generally corresponds to something that might be done on a manual control. Manufacturers do not reference a common way of constructing recommended sentences, though they generally follow the format of <command> <object> <value/state>, e.g. “turn the kitchen light off.” It would seem fairly simple for such systems to accommodate a variety of word orders.

Commands commonly found are: Turn on, Turn off, Dim, Brighten, and Set (to a percentage value). Example other phrases found are: "Turn <light name> green", “Turn on/off all of the lights”, and "Set <light name> to green". Lights and rooms (which contain one or more lights) have names, which are presumably set locally but with some being common names (e.g. “Kitchen”, “Master bedroom” and some being house-specific (e.g. “Maria’s room”).

One device (Alexa from Amazon) knows about several “Shades of White”: “Warm white”, “Soft white”, “White”, “Daylight”, and “Cool white” (as warm and cool are on the end, and plain “White” in the middle, this is likely in order). It also has “Available Colors” of “Blue”, “Crimson”, “Cyan”, “Fuchsia”, “Gold”, “Green”, “Lavender”, “Lime”, “Magenta”, “Lime”, “Orange”, "Pink", "Purple", "Red", "Salmon", "Sky Blue", "Teal", "Turquoise", and "Violet". Both of these could be standardized for the word/phrase to use and the specific color attached to that word.

4.1.3 Indicators and other Feedback

Indicators should follow traffic signal light standards when distinguishing among red, green, and/or yellow, to enable those who are color-blind to be able to distinguish among them.

Some occupancy sensors use a red indicator to show when an infrared sensor is active. Should this be an allowed or encouraged exception to the 'no red' rule?

Indicators should generally not flash in ordinary operation so as not to call the user's attention unless needed. An indicator which calls attention to itself with dynamic behavior when not warranted is pointlessly distracting and can be annoying.

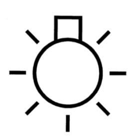
Non-speech audio and haptic feedback should not be the sole interface mechanism used to ensure that people who lack some or all abilities with these can still utilize the control.

Some devices include a 'locator light' to be able to find the control in the dark. A range of colors are currently in use but a white light seems the most neutral, and the key to a locator light is that is not trying to communicate any status information. Other colors are generally used to indicate something (see 4.5.1); thus, white seems to be the best choice for locator light color but the case is not so ironclad that other colors should be ruled out.

Should there be a standard symbol for 'locator light'? The need for one is not obvious.

4.2 Lighting in General

The most common symbol for the overall concept of lighting in general is a traditional bulb shape with emanating rays. The standard symbol for lighting in general should be IEC 5012 as shown in the figure below. It is defined as "To identify switches which control light sources, e.g. room lighting, lamp of a film projector, dial illumination of a device." Note that the symbol refers to the control, not to lighting itself, presumably as it is a label for the control. Most of the examples of the lighting symbol we found had seven rays, though a few had five, six, or nine. In addition, the symbol was found with the base up in some cases and down in others. So, while controls for sale vary the number and length of the rays, shape of the bulb, orientation (pointing up or down), and color, the ultimate key is whether the user clearly recognizes the symbol's meaning.



IEC symbol 5012

Some controls use a light symbol with no rays to indicate off. Should this be explicitly encouraged or discouraged?

This raises an issue about how much the user can effectively incorporate information about the context in applying symbols; this standard assumes they can to some degree. It is assumed that users understand the symbol to mean Light or Lighting, and when they see it next to a control, they will associate that meaning with the control. It is not assumed that people will think that the symbol means only the control is a light. This principle arises later when the idea of Occupancy is used on a sensor, in which case the user is assumed to combine the two ideas.

Over time we may expect an overlap and blurring of distinction between lighting and information displays. Both are now based primarily on the same technology, LEDs. We will increasingly see displays as a source of light, and the ability of lights to modulate intensity and color, and organize many individual sources, makes them increasingly available to convey information. Use of common concepts and elements between displays and lighting is therefore helpful, e.g. brightness.

4.3 Basic Switching

As most lighting is changed through mechanical motion of the user, consistency in this across lighting controls, and across controls in general, is needed. The ISO mechanical associations (see Section 4.1.1) are sound and should be followed. There are some countries that conventionally use up to mean off. Over time, these countries should shift to consistency with the ISO standard. During the transition, the on and off symbols can be used to clarify how any particular control works.

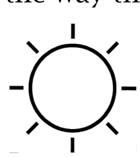
For applications in which the On I and Off O symbols alone or as a pair may be unclear to the user, the Power symbol ⏻, is recommended and should be used to toggle the power state. There is a second symbol, ⏼ which is for use when the off position is zero power, but this fact is known by very few people and would likely usefully inform even fewer so that use of this symbol is not recommended for use, even when technically correct.

Controls for setting ramp or fade functions (short transitions between on and off, or between different brightness levels) are rarely present in user interfaces so the standard makes no recommendation on them.

4.4 Brightness

The basic symbol for variable control, ISO 5004, is defined as "To identify the control device by means of which a quantity is controlled." This matches what is needed for controlling the level of light output.

Changing light levels first came into common use with "dimmers," which operated by reducing light output down from its maximum level. Thus, dimming emerged as the organizing metaphor. However, brightness is really a better choice as it speaks directly to what is involved rather than a mechanism to change it. "Brightness" is the noun (the result), the underlying concept. "Dimming" is a verb (the action), the way that one changes the light level.



IEC symbol 5056: Brightness

The brightness symbol (figure above) is used on many TVs, so has some familiarity to ordinary users. The symbol does have some similarity to representations of the sun (including to the 'natural light' symbol for use in photography), so it is important to not increase the number of rays used or their length, as that would blur the distinction between the symbols.

There are products on the market that use a large and small version of the brightness symbol, or one with longer and shorter rays, to indicate greater and lower brightness levels. There are products which pair the brightness symbol with the brightness symbol without any rays, which is just a circle, and so the off symbol.

Should some or all of these be explicitly encouraged? discouraged?

As daylight sensing becomes more prevalent in buildings, it will be important to clearly distinguish a symbol for daylight sensing from brightness (see Section 4.5.2).

It seems likely that users would most commonly want a light turned on to return to the most recent brightness level, and while most controls are likely to operate this way, it is not clear that this should be mandatory.

4.5 Dynamic Control

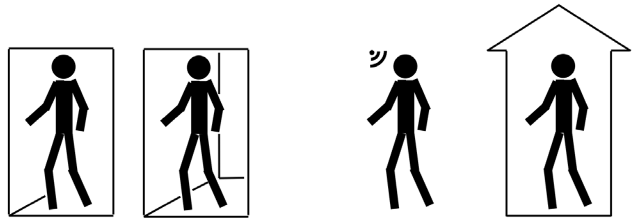
Changing on/off state or brightness level with occupancy sensing is common today; daylight sensing is becoming more common. Within each there is the concept of the sensor, and control being dependent in part on the signal from the sensor. Control might also be enabled or disabled. Indicators can show status of sensing (e.g. if an occupant is detected or not), and whether sense-based control is enabled or not. In summary, there is the underlying physical condition, and the sensing of that condition.

4.5.1 Occupancy Control

Existing symbols for occupancy sensing (found mostly on marketing materials rather than on products themselves) tend to show an abstract person walking along with emanating rays from above (see figure below). The walking attribute distinguishes these symbols from a stationary person as is used with the restroom symbols. A walking symbol will be distinguished from a running person, which is commonly used as an exit symbol in Europe and perhaps elsewhere.

Human-oriented occupancy sensing symbols: first from interface; the rest from marketing materials.

The recommended symbol is the first one in the figure below; its only advantage over the second is being graphically simpler. It is intended to show a person in a constructed space (room). Having the person in a dynamic pose differentiates the symbol from the standard bathroom symbol in which the person is facing the viewer. Traditional occupancy sensors sense movement, but this may not be true of future sensing technologies (e.g. imaging). Other alternatives considered are the last two, which employ the sensing attribute (which per above is not necessarily desirable to include), and an alternate version of a person being in a space (though this one may more convey the notion of a restroom).



Occupancy Symbols

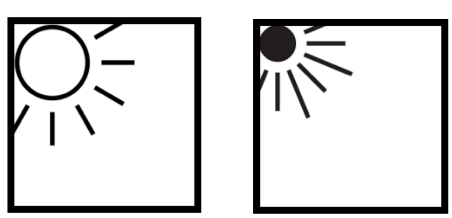
The ISO and IEC symbol standards do not include any that mean Occupancy specifically but include several worth referencing (many of the rest are for medical or safety applications). The first symbol in the figure below is an existing safety symbol that shows a person walking;[3] it is "To signify that pedestrians must use a designated walkway," and is a "Human figure walking (left hand)." [ISO] The second image is "To instruct persons to move forward," which without the arrow is a good model for a person moving. The third is for an emergency exit, "To indicate an escape route to a place of safety" and is a "Human figure moving (to the left) through doorway."

ISO M024 - "Use-this-walkway"; ISO PI BP 019 - "Proceed forward"; ISO E001 - "Emergency-exit-(left-hand)"

For indications on occupancy sensors, using red for infrared sensing has an obvious clarity. However, red is supposed to be used for an error or warning, and so this would require an exception to this general rule. In the long run we may well move onto other technologies; tying this indicator color to a single technology seems ill-advised. Labeling with a symbol would be better. However, as occupancy sensors are commonly mounted on the ceiling or otherwise high up, symbols may not be readable without a ladder.

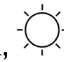
4.5.2 Daylight Control

We propose that the first symbol below be used for daylight sensing or control. The second was considered but the filled-in circle seems less clearly the sun, though the variable-length rays do convey a sense of variability that is helpful.



[3] For an artistic take on "Walking Men," and an excellent collection of images of pedestrian traffic signals, see: http://walking-men.com/.

Daylight Symbols

For daylight sensing, technically such systems are sensing and then acting on ambient light, which may be from daylight, or from other artificial light sources. However, as the primary application is to reduce energy use of artificial light by taking advantage of freely available daylight, the daylight metaphor is used. The brightness symbol, , has a resemblance to the symbol for "Natural Light" , but the 'sun' symbol has longer and more rays. The natural light symbol was originally for cameras, not light sources.

The ILV states that "17-285: daylighting: lighting for which daylight is the light source. NOTE Formerly "natural lighting" was used, but "daylighting" is in use corresponding to use of "electric lighting."

4.5.2 Time-based Control

Technically, the symbol for Date , indicates a control to set the date, but it seems broadly understood to refer to calendar issues in general. There are additional symbols that are variants of the Clock/Time symbol  for setting a start time or duration of an activity, but an average user is not likely to make the fine distinctions between them or know or intuit their diverse meaning. As both symbols ultimately refer to time, either seems suitable for indicating that type of control for absolute time.

There is a standard symbol for self-timer,  for use on cameras. This might be useful in some lighting applications and could be used and could be added to the standard.

4.6 Color

The color symbol, , has been used on television controls in the past. It may not be widely recognized but has an intuitive clarity.

For color temperature, there is the unfortunate fact that cool white colors are a higher color temperature than warm whites. Few ordinary people know this, it is contrary to temperatures that people experience in daily life, and "correctly" having a horizontal scale of color temperature would put warm at the left and cool at the right (and in fact there are lighting controls sold currently that do this). If this were to be deployed widely, it would likely be a significant source of confusion. Since the temperature in color temperature is not something people actually experience (as the measures of it in thousands of K show[4]), it ends up being an abstraction for people and so not particularly helpful. People do not experience color temperature in a way at all similar to how they perceive air or water temperature. It would be

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[4] The ILV defines "17-231: colour temperature [Tc]: temperature of a Planckian radiator whose radiation has the same chromaticity as that of a given stimulus. Unit: K. NOTE The reciprocal colour temperature is also used with unit K-1 or MK-1 (where 1 MK-1 = 10-6 K-1) whose previous name "mired" is now obsolete."

better to have an alternative metaphor which has the right progression for greater value. Hence, the choice of color time.

In the morning the air temperature is cool, and with frost or condensation from breath, one sees cooler white colors. In the afternoon there is sunset and sometimes in the evening fires, which both convey warm colors. This use of time as the underlying metaphor seems to well match ordinary human experience and is consistent with physical mappings as warmer is then associated with more. Note that the terms cool and warm can still be used - just the notion of temperature is dropped.

4.7 Other Topics

In most cases of shading control, more or less translates to up or down, which can be counterintuitive as it might not correspond to the motion of the shade device. A roller shade (or venetian blind) that comes from the top will be moving down when the shade control is set to increase. While this might seem counterintuitive, it does mean that the control is the same whether the shade originates at the top, bottom, side, or is electrochromic and originates across the entire window.

5.0 Topics for further study

Lighting “scenes” are certainly useful for control but seem likely to introduce complexity and therefore frequent confusion. However, no clear content on scenes is apparent to include at this time.

All controls, including lighting, should be as accessible to those with a variety of disabilities as much as is feasible. Research to date has not surfaced good content to include on accessibility but those involved in lighting control research should be attentive to any that arise.