Adaptive Lighting for Energy-Efficient Comfort and Wellbeing

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Abstract

Adaptive lighting refers to electric lighting sources that automatically adjust their output based on environmental changes, aiming at maximizing comfort, wellbeing and energy efficiency. This presentation provides an overview of the concept, focusing on adaptive lighting controls based on sensing occupancy and daylight. The overview reflects the adaptive lighting research, development and demonstration efforts of the California Lighting Technology Center. The adaptive lighting efforts were initiated in 2003 and continue today, having produced significant results and multiple commercial products. The goal of the efforts is to maximize electric lighting savings by automatically controlling electric lighting based on occupancy and daylight. The focus is on strategies and technologies to improve performance in terms of reliability and cost-effectiveness for wide-spread use in outdoor and indoor spaces of new and existing buildings.

Author Keywords

Electric Lighting; Daylighting; Occupancy Sensor; Motion Sensor, Photo Sensor; Demand Response; Control Algorithms; Adaptive Lighting; Smart Lighting; Smart Luminaires.

1. Introduction

The California Lighting Technology Center (CLTC) was established in 2003 through a partnership among the Department of Energy (DOE), the National Electrical Manufacturers Association (NEMA), the California Energy Commission (CEC) and the University of California, Davis. Its mission is to accelerate lighting and daylighting technology transfer from the laboratory to the market place to help reduce building and community energy requirements for electric lighting and HVAC.

Energy-efficient lighting: The fundamental lighting design strategy is to provide the *right light* at the *right place*, at the *right time*. *Right light* refers to the spectral power distribution (SPD) of *light sources*, i.e., providing only the parts of the visible spectrum needed to best serves space activities. *Right place* refers to the candle power distribution (CPD) of *luminaires*, i.e., providing appropriate luminous flux where it best serves space activities. *Right time* refers to *lighting controls*, i.e., adjusting the SPD and/or CPD of light sources based on changes in environmental conditions in the space being served. Adaptive lighting is the automated implementation of this fundamental lighting design strategy, aimed at optimizing comfort, wellbeing and energy efficiency.

Most of today's lighting controls address the CPD of light sources by adjusting total light output of light sources. Controlling the SPD of light sources is a relatively new concept that is entering the market fast, as new knowledge emerges about important non-visual effects of light on human health, and new strategies and technologies are being developed that support luminaires with dynamic SPDs and appropriate SPD management for health and wellbeing benefits in different applications.

Adaptive lighting was a key focus of the CLTC when it was established, in 2003. Initial efforts included the development of a residential porch luminaire that automatically adjusts both CCD and SPD. The adaptive luminaire includes a high-output white light source and a low-output amber light source, along with integrated photo and occupancy sensors. The photo sensor signal is used to keeps both light sources off during daytime and turn them on during nighttime. The occupancy sensor signal is used to turn the high-output white-light source on during occupancy periods and off during vacancy periods (Figure 1).

Figure 1. Commercial adaptive outdoor luminaire for residential porch applications, showing night time operation during occupancy (left) and vacancy (right).

This presentation is focused on research and development efforts towards automated CPD changes, i.e., adjusting the light output of electric lighting sources through switching and dimming, based on occupancy and available daylight. More specifically, the presentation is focused on the use of motion sensors to detect occupancy and photo sensors to detect daylight levels. The presentation is focused on the key challenges and related strategies and technologies that are being considered towards successful implementation in terms of reliability and cost-effectiveness.

2. Adaptive Lighting Based on Occupancy

Occupancy-based controls aim at minimizing electric lighting energy during vacancy periods, either by turning lights off or diming them to a low level, depending on application.

The key challenge in occupancy sensing is reliability. Occupancy has been traditionally detected using motion as a proxy. Several motion sensing technologies are in use today, using strategies based on passive infrared (PIR), ultrasonic and microwave sensing. Significant efforts are also under way to detect occupancy through video-stream analyses but have not yet achieved wide-spread use, mainly because of privacy concerns, response time and cost.

Today's occupancy-sensing strategies include combinations of motion sensing approaches, and, most important, networked sensing that provides excellent opportunities for increased reliability and effectiveness, i.e., turning lights on in expectation of occupancy, based on signals from multiple sensors in the network. This is especially useful in outdoor applications, when reacting to sensing at the location of the light source may not be fast enough to be effective. Many outdoor applications, such as street parking lots and garages, require sensing vehicles, which can be moving at high speeds. The same is true for pedestrian pathways with runners and bicyclists. Predictive motion controls are also useful in applications where motion is initiated very close to the motion sensor, resulting in late response, such as occupants entering a space or turning the corner around a building.

Work in this area was initiated in 2005, focusing on the development of occupancy-based adaptive luminaires for outdoor applications, initially for outdoor and then for selected indoor applications that offer opportunities to realize significant energy savings without negative effects on comfort.

Outdoor applications: The CLTC work on outdoor lighting controls was initiated after extensive photographic documentation of outdoor spaces in the UC Davis campus, which indicated that most outdoor spaces, including streets, pathways, parking lots and garages, were vacant during most of the nighttime, yet illuminated at full light output. This opportunity started work initially for parking lot applications, aiming at development of occupancy-based controls that would provide 100% light output during occupancy and 50% or less during vacancy. Initial field demonstrations of prototypes were very successful, however with significant challenges of controlling high intensity discharge (HID) light sources of that time.

The introduction of LED lighting for outdoor applications resolved the issue of controlling light source output and resulted in multiple commercial occupancy-based adaptive street and area luminaires. CLTC participated in many demonstration studies, throughout the years, which showed significant energy savings, but also revealed limitations, such as sensing distance and response time, especially for fast-moving objects. The strategies to addressing them were focused on sensor networks, i.e., adding network communication capabilities to each adaptive luminaire, allowing them to share geolocation and motion sensing status. This information is used to determine direction and speed of moving objects, so that luminaires are turned on in anticipation of expected motion.

Initial studies and analyses at UC Davis showed potential not only for energy savings but also for significant economic benefits through reduced maintenance and safety benefits through support for real-time observation of motion activity. In 2010, UC Davis decided to implement the approach across the whole campus as part of a larger Smart Lighting Initiative that included interior lighting controls as well. Today most of the outdoor lighting at the UC Davis campus is provided by networked adaptive luminaires, providing energy savings in the range of 70% compared to the non-adaptive incumbent HID technology [15].

By 2013, there was wide availability of multiple commercial technologies and plenty of studies showing consistent energy and non-energy benefits, at continuously reduced cost. Occupancy-based adaptive outdoor lighting met the requirements for consideration for inclusion as a requirement of the California building energy codes. It was proposed as a measure and today has been adapted as a requirement, for luminaires that are mounted lower than 24 feet from the ground. This height limit was based on concerns about reliability of available technologies in sensing motion at long distances, such as those between consecutive poles when luminaires are mounted higher than 24 feet. Efforts are currently underway to develop strategies and technologies to improve motion sensing reliability from long distances, for street and area lighting.

Indoor applications: Motion sensing in indoor applications is relatively easy, as occupants are usually the only moving objects in the space. They have been successfully implemented for many indoor spaces. Occupancy controls are required or encouraged by most building energy codes for most interior spaces, providing significant energy savings, especially in places with long vacancy periods.

The CLTC has participated in multiple installations and demonstrations focusing on spaces that have not been addressed in the past, such as stairwells, corridors and hallways. These spaces offer significant opportunities for energy savings, as are usually illuminated fully continuously, while they are vacant for long periods of time, especially during the night. The control strategy for these applications aims to provide full illumination during occupancy, and low-level illumination during vacancy, to ensure safety. Field measurements indicate significant energy savings, closely following occupancy patterns [16][17][18].

The main performance limitation is inability to sense very low motion activity, as in spaces with occupants that are stationary with minor movements, such as office workers working on a computer. Another limitation for open office application is limiting sensing distance for applications in individual cubicles in an open office environments.

3. Adaptive Lighting Based on Daylight

Daylight-based controls for electric lighting aim at adjusting electric lighting output based on available daylight, offering opportunities for significant energy savings in commercial applications, as well as peak electricity demand reduction.

Bi-level control for window applications: The work in this area was initiated in 2005, responding to the California Energy Commission and California utilities for simpler, bi-level switching controls for 50% light reduction, with reliable and cost-effective operation.

The initial laboratory experimentation focused on characterization of available technologies in terms of photo sensor directional sensitivity and, most important, quantification of the effect of the geometry and reflectance of interior surfaces, which significantly affect the signal of photo sensors in the space. As the surfaces in the photo sensor view can vary dramatically through time in most applications, it presents a significant challenge and explains the need for often recommissioning, which was by far the most expensive part in most installations. Placing a white table under a photo sensor that was commissioned seeing a dark grey carpet will most probably results in over dimming, as the change in the signal of the photo sensor reflects change in geometry and reflectance of interior surfaces rather than change in daylight levels in the space.

Trying to address the commissioning issue, efforts were focused on the development of a different algorithmic approach for the calibration of the lighting control system that supports automated calibration. The new algorithm is based on the photo sensor signal differences between consecutive light output levels, i.e., 0%, 50% and 100%. These differences are then used to define OFF and ON set points for the switching of the light source(s). A safe distance between ON and OFF set points to avoid cycling and a relatively long time response to account for occupant effects in the view of the sensor proved to both reliable and cost-effective, performing the quick and easy automated calibration either during the nighttime or on demand, through manual signal.

The automatic recalibration can also be used during operation, each time the lights are switched from one state to the next in sequence. The different would reflect that status of the space at that time. However, this can only be realized after a possibly wrong action was taken. Most important, it would be very challenging to use for diming applications, where the changes in sensor signal between consecutive states are very small. The research and development results were pointing to the need for at least one additional photo sensor, which would greatly improve reliability and support continuous, automated calibration during operation. The additional photo sensor can be open- or closed-loop, i.e., affected by the electric lighting it controls or only by daylight, respectively. Both approaches have been implemented for dimming controls, using a closed and an additional open-loop sensor for skylight applications and two or more closed-loop sensors for window applications.

Dimming control for skylight applications: Work on photo sensing controls for skylights was initiated in 2006, responding Walmart request for improved reliability in sensing daylight changes for diming controls in their stores.

Walmart has been using skylights and photo-sensor controls for electric lighting in most of their stores since 1995. Soon after the initial implementation of closed loop systems in their stores, Walmart realized their major limitation, i.e., the effect of interior surface reflectance on the signal of the photo sensor. After several months of multiple requests for recommissioning, following changes in the store displays seen by the sensor, Walmart decided to use open loop sensing, i.e., sensing daylight through a sensor mounted under one of the skylights and looking towards the sky, not being affected by changes in the space. This is the approach still in use today, but with consistent complaints about short dimming times during sunrise and sunset and problems during partly cloudy days.

To differentiate between daylight changes and space changes, efforts focused on developing a two-sensor control system specifically for skylight installations, referred to as "dual loop". One of the sensors is used for closed-loop sensing, monitoring light level changes in the space. The other sensor is used for open-loop sensing, affected only by daylight changes, as it monitors the light coming from the sky. Both sensors are placed under one of the skylights, the closed loop looking down and the open loop looking up. The combination of the two signal streams is then used to effectively differentiate between true daylight changes and changes in the geometry and reflectance of interior surfaces. The automatic calibration algorithms were expanded to address diming and also implement continuous automatic calibration during operation for the closed loop sensor,

After extensive testing in the laboratory considering multiple alternative scenaria of space and daylight changes, a laboratory prototype was installed and operated at the West Sacramento Walmart store, controlling one quarter of total store lighting. The other three quarters of the lighting were controlled based on the signal of the standard open-loop system used in most Walmart stores. The operation of both systems was monitored over a period of one year and offered the opportunity for comparative evaluation if the two control systems under almost identical daylight conditions. The results showed that the dual loop improved performance over the open loop by providing about 50% more energy savings and, most important for Walmart, eliminating complaints from occupants [19].

Dimming control for window applications: After the success of the dual-loop system for skylights, the approach was tried for spaces with windows, which are significantly different than spaces with daylight in terms of interior daylight levels. Daylight levels in spaces with windows drop significantly by distance from the windows. Moreover, windows are usually equipped with window attachments, which are operated by building occupants and affect daylight levels and the signal of both photo sensors. While the efforts were successful in the laboratory, the approach did not have promise for market success, as the location of the open- and close-loop sensors required significant commissioning. This was especially true for the equivalent of the "open-loop" sensor, whose proper position and field of view greatly depends on the type of window treatment.

Considering solutions that resolve the issue of photo sensor placement on site, CLTC explored the used of multiple closed loop sensors, each monitoring light levels at different parts of the space. The approach can be used with two or more sensors in individual, autonomous luminaires, or with one closed loop sensor per luminaire in spaces with more than one luminaires that communicate with each other. The assumption of the approach is that similar space changes at two or more different parts of the space at the same time are highly unlikely. The research efforts focused on exploring the use of multiple luminaires with integrated sensors, considering eight different sensor locations for each luminaire. The laboratory prototype system includes four luminaires and works effectively. However, the approach has not yet been tested under extensive and challenging scenaria of space and daylight changes.

4. Daylight Management Integration

The challenges in saving electric lighting through available daylight are not only technical in nature, like the ones addressed in the previous section. A significant challenge to realizing the potential electric lighting savings is behavioral in nature, as occupants are usually responsive to nuisances, but not to opportunities. Most occupants adjust window treatments for privacy or glare reduction, e.g., to block direct sunlight penetration, which may dramatically reduce interior daylight levels, causing increase in electric lighting output. After the privacy need or the glare condition have passed, most occupants will readjust the window attachment for view, while very few will readjust it for daylight penetration and electric lighting energy savings.

One way to resolve the issue of manual management of window attachments is to automate their operation based on sensing their environment, i.e., developing adaptive window systems. Most operable windows and skylights, such as those with Venetian blinds, roll-down shades and dynamic glazings, can become adaptive. In additional controlling their visible transmittance, which has direct effects on electric lighting savings, adaptive windows and skylights can also control solar transmittance and even natural ventilation and cooling, aiming at HVAC energy savings.

Adaptive windows are significantly more complicated than adaptive lighting, as they affect multiple performance aspects, including occupant-driven for view and privacy and electric lighting and HVAC savings, both of which can be automated. HVAC savings include not only cooling and heating loads, but also natural ventilation through openable windows. Work focused on experimentation with prototype systems in the laboratory, using electrochromic glazings and roll-down shades, operated based on sensing interior and exterior environmental conditions, such as occupancy, light levels, temperature and humidity.

Unlike with electric lighting and HVAC controls, effective operation of window and skylight adaptive controls requires communication with the lighting and the HVAC systems, as it needs to know their state to determine appropriate function towards reducing energy loads.

The CLTC is currently working on a project aiming to develop an integrated solution of electric lighting, window, skylight and HVAC controls, bringing together commercially available technologies and focusing on the development of algorithms that will enable integrated operation that is also harmonized with manual operation, which is most important for market acceptance. All controls are based on the same simple control strategy of prioritizing comfort during occupancy and energy efficiency during vacancy.

The integration of sensors in electric lighting luminaires can be extended to include occupancy, temperature, humidity and other sensors that provide important information not only for lighting but also for HVAC and indoor air quality. The availability of electricity at the luminaire level makes it an obvious place for sensor hubs and there are several commercial products that provide multiple sensors integrated in luminaires, or sensor hubs that are associated with individual luminaires on site.

5. Conclusion & Next Steps

Adaptive lighting systems show significant promise for reliable and cost-effective operation of electric lighting systems that provide electric lighting savings without negative effects on comfort.

Indoor occupancy-based controls are widely spread and effective in most interior applications. Improvements in motion sensitivity are still needed for sedentary spaces, along with technologies for short-distance motion sensing, e.g., for task lighting control in individual spaces of open office environments.

Outdoor occupancy-based controls have more challenges, not only because of they are exposed to a wider range of environmental conditions but also because of the need for faster detection times for fast-moving objects such as vehicles. Microwave, sensor networks and alternative approaches from other industries, such as video-based controls and lasers, show promise to resolving such response time issues but have yet to be tested.

Daylight-based control issues have been mostly resolved for skylight applications but have not yet been validated in field installations of commercial products. Plans are under way validate a commercial dual-loop installation at the West Sacramento Walmart store.

Daylight-based control issues have not been resolved for dimming applications in spaces with windows. However promising strategies based on existing technologies are addressing the two remaining challenges: the reliable detection of interior daylight changes and the occupants' behavior in adjusting daylight penetration through windows for view, privacy and glare reduction purposes, most often left in positions that block daylight, resulting in significant reduction of lighting energy savings. The first challenge is being addressed through use of multiple closed loop sensors, either in one luminaire or multiple, networked luminaires. The second challenge is being addressed through development of adaptive windows, which can automatically adjust their daylight and solar transmittance to manage daylight penetration, considering the state of the electric lighting and HVAC systems and the potential for glare from direct solar penetration.

Eventually, luminaires, windows, skylights and HVAC components and systems will be part of the *Internet of Things*, which will offer opportunities for even more effective controls, as they will have access to more of the required information about their environment for more reliable and cost-effective operation.

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