research MATTERS

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Daylight harvesting is a great strategy to save energy, focusing on partially or completely reducing electric lighting when daylight is available in commercial and industrial buildings. Most importantly, daylight harvesting greatly contributes to peak electricity demand reduction, as its availability coincides with peak demand.

Architectural and interior designs are critical for successful daylight harvesting, with respect to providing daylight in effective and efficient distributions over space and time for different geographical locations and architectural spaces. The daylight and electric light distributions in a space are critical for successful implementation of electric lighting controls, especially photo sensor-based controls, which is the main focus of this article.

The objective of this article is to offer a closer view of the main issues and potential resolutions in photo sensor-based daylight harvesting controls. Even though photo sensor-based controls are simple as theoretical concepts, they can be difficult to apply in practice.

BARRIERS & ISSUES

The main barriers to effective daylight harvesting are *reliability*, especially over time, and *cost-effectiveness*, not so much because of the cost of technologies, but mostly because of the expensive labor required for commissioning.

Commissioning. The commissioning process aims at calibrating the photo sensor controls to match the geometry and surface reflectance of the daylit space and adjust the system to reduce electric lights as much as possible without negative effects on luminous comfort. Commissioning is usually performed after the system is installed. Unfortunately a single commissioning process cannot ensure sustained successful operation. Changes in the geometry and surface reflectance of the controlled space may affect the operation of the control system, requiring re-commissioning.

Even though photo sensor-based daylight harvesting controls are simple as theoretical concepts, they can be difficult to apply in practice

Consider the commissioning for a ceiling-mounted photo sensor system performed in an empty space with a dark-color carpet. If, during occupancy, a light-color table is placed under the sensor, the control system will result in over-dimming, i.e., the system will interpret the increased photo sensor signal as increased daylight level. To operate properly, the system needs to be re-commissioned. This is the case for every change in the space that affects the signal of the photo sensor.

If changes in the space result in under-dimming, the problem is rarely detected, resulting in missed energy savings. If the changes result in over-dimming, then occupants get disturbed. If the problem is understood, it can be corrected through re-commissioning; if the problem is not understood, the system is disabled, eliminating the opportunity for energy savings and peak demand reduction.

Single-sensor approaches. Single photo sensors can also be ineffective in determining indoor daylight levels. Closed-loop photo sensors, i.e., monitoring the controlled area and affected by the controlled electric lights, cannot reliably account for daylight changes because they can't differentiate between true daylight changes and changes in the geometry and surface reflectance in their field of view. In addition to sustained changes over time, such as the table example presented above, there are also transient changes, such as people with clothing of varying reflectance moving in the space. The magnitude of the transient change problem is greatly affected by the placement and angular sensitivity of the control photo sensor.

Open-loop approaches, where the photo sensor is not affected by the electric lighting being controlled (i.e., it does not "see" the controlled space and is not affected by long- or short-term changes in the space). However, they are affected by changes in the outdoor levels that may not necessarily affect indoor daylight levels, as is the case during early morning and late afternoon or early evening hours, as well as during partly cloudy days.

Photo sensor angular sensitivity. The objective of control photo sensors is to measure the changes in daylight levels. Their signal, however, is the result of light reflected off the surfaces that they see. Depending on their angular sensitivity, they weigh light from different directions differently. An illuminance meter, for example, weighs the light coming from each direction by the cosine of the incident angle. This means that changes in areas viewed by the sensor in small incident angles are weighed significantly more than low incident angle directions and the operation of the system follows mostly what happens in front of the sensor.

Transient changes can significantly affect the signal of the control photo sensor depending on the angular sensitivity of the photo sensor and its distance from the transient changes. A person with black clothes passing under a cosine-corrected control photo sensor integrated in a pendant fixture can reduce the photo sensor signal by as much as 80 percent! To account for such transient changes, current systems incorporate time delays, which are not really solutions, as they are also applied during true daylight changes.

POTENTIAL RESOLUTIONS

The California Lighting Technology Center (CLTC) research efforts have resulted in three technological innovations aimed at increasing the reliability and cost-effectiveness of photo sensor-based daylight harvesting controls. The CLTC research is supported by the Public Interest Energy Research (PIER) program of the California Energy Commission (CEC).

Automated continuous calibration. Traditional photo sensor control approaches are based on the relationship between the signal of the control photo sensor and work plane illuminance. The location of the work plane illuminance measurement is critical to the operation of the system and is an unknown factor, i.e., it is not known during commissioning and, even if it is, it can certainly change over time. Most importantly, work plane illuminance is not really a good metric for visual comfort.

Elimination of work plane illuminance from the control algorithms has led to an approach focused on the differences in the control photo sensor signal caused by sequencing the controlled electric lights through its available light output levels. These differences are measured very easily at any time for on/off, stepped switching and continuous dimming applications. Since they are also continuously measured during the actual operation of the system, this approach allows for automatic continuous calibra-

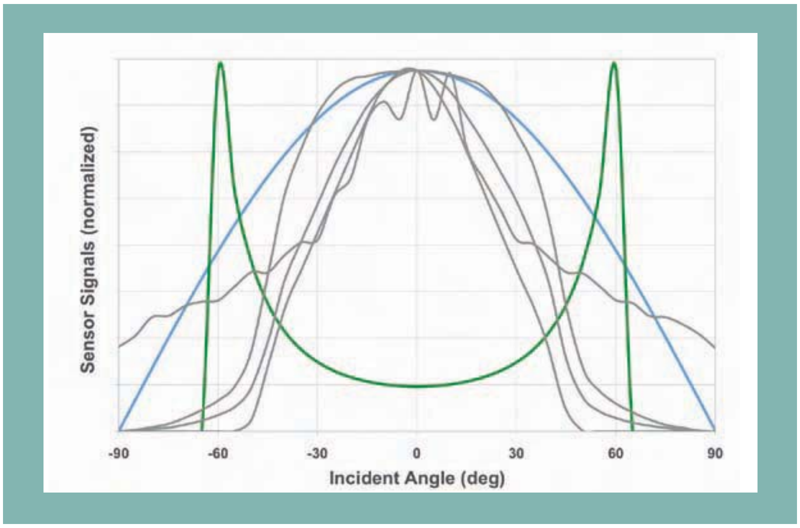

Figure 1. Angular sensitivities of various commercial control photo sensors (gray lines) compared to the corresponding cosine sensitivity of illuminance meters (blue line) and a theoretical sensitivity that aims at a flat response to light reflected off the floor towards a ceiling mounted sensor with a cut-off angle of 75 deg (green line).

Figure 2. The CLTC side-lit daylighting laboratory during testing of a luminaire-integrated photo sensor prototype for bi-level daylight harvesting controls.

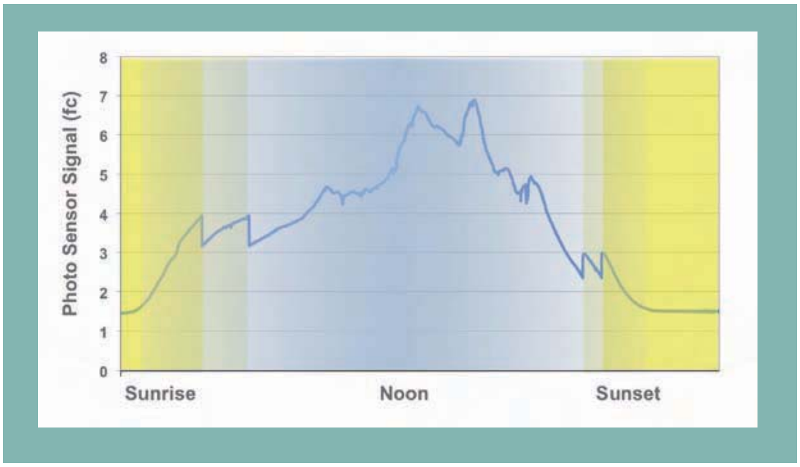

Figure 3. The control photo sensor signal of the luminaire-integrated bi-level control system shown in Figure 2, which turns the lights at 50 percent and 100 percent based on available daylight. The data are for a winter day and the lights stay off for most of the day.

tion, accounting for any changes in the space geometry and surface reflectance. As a result, automated continuous calibration has the potential to eliminate commissioning, which is the most expensive part of current daylight harvesting approaches.

Reliable, dual-sensor systems. The single photo sensor shortcomings were addressed through use of two photo sensors, aimed at different areas in the space that are unlikely to be simultaneously affected by changes within the space. The dual sensor approach is necessary for effective, reliable continuous dimming and recommended for on/off and stepped switching.

Stepped switching (usually on/off, bi- or tri-level systems) may work effectively with a single photo sensor of appropriate angular sensitivity and a relatively long time delay in implementing changes. These systems usually switch lights down sometime in the morning and up sometime in the late afternoon or early evening, depending on the season. A long time delay, such as five-plus minutes, will have a small effect in the overall performance of the system, i.e., it's okay for the lights to turn off at 8:35 a.m. rather than 8:30 a.m. if this will reduce the chances of transient changes producing unwanted switching.

Customization of photo sensor angular sensitivity. Traditionally, we have been considering the field of view of the photo sensor, but not the angular sensitivity within the field of view. In most cases, the angular sensitivity of the photo

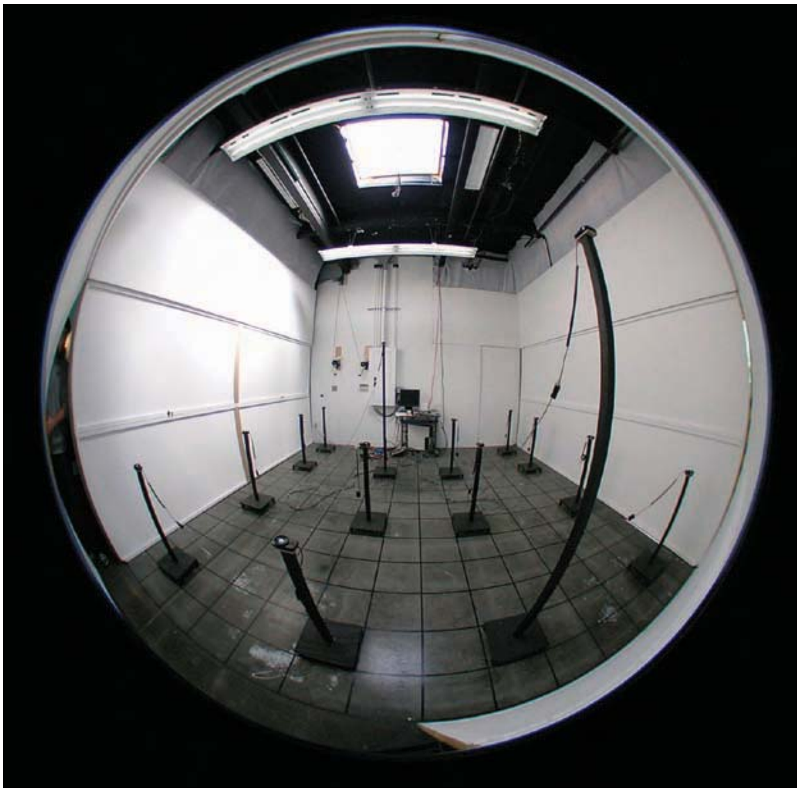

Figure 4. Dual-loop, dimming daylight harvesting controls being tested at the CLTC top-lit daylighting laboratory. Initial results are promising in increasing the reliability of monitoring daylight changes.

sensors is not known and can vary significantly. Most photo sensors tend towards the cosine sensitivity and are not appropriate for daylight harvesting controls because they provide a weighed rather than a flat averaging for the daylight in the space. The sensitivity for a theoretical flat response of a ceiling- or fixture-mounted control photo sensor, accounting for both the incident angle and the distance to the sensor, is pretty much the reverse of the cosine sensitivity (**Figure 1**). A flat-response sensitivity would minimize the effects of horizontally moving surfaces within the field of view of the photo sensor.

CURRENT STATUS

Research involving industry partners continues at the CLTC side-lit and top-lit daylighting laboratories. One prototype being pursued is a simplified, single-sensor bi-level system (**Figures 2 & 3**). Other commercial prototypes focus not only on stand-alone sensors used to control multiple luminaires, but also on luminaire-integrated sensors, which offer excellent opportunities for optimization of angular sensitivities at the factory. Moreover, they offer excellent opportunities for increased cost-effectiveness, as the incremental cost of the embedded sensors and controls is very small.

A prototype of a two-sensor approach for skylights is also being tested in the top-lit laboratory (**Figure 4**). One photo sensor "looks" through the skylight at the sky (open loop) and the other at the floor below (closed loop). The simultaneous signals from the two photo sensors successfully allow differentiation between daylight changes and transient space changes.

Successful laboratory testing of the commercial prototypes will be followed by field testing in partnership with the California utilities.

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