Cost Effective Simplified Controls for Daylight Harvesting

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ABSTRACT

Most commercial spaces have enough daylight next to windows to eliminate the need for electric lighting. Daylight harvesting systems automatically dim or switch electric lights depending on daylight availability, offering significant energy savings. Most important they offer significant peak demand reduction, since peak demand usually occurs during the highest levels of daylight availability.

Dimming electric lights based on available daylight is expensive with significant equipment (dimming ballasts) and commissioning costs. To date, only a small fraction of side-lit dimming applications operate satisfactorily. While useful in low daylight areas, dimming is not really necessary in areas with high levels of daylight where dimming is only useful during the early morning and late afternoon.

This paper focuses on the development and laboratory testing of a new Simplified Daylight Harvesting (SDH) approach designed to operate as a bi-level lighting system and applicable to existing bi-level systems, which have been required in California by Title 24 since 1983. The SDH system works "out of the box," i.e., without need for either calibration or commissioning.

SDH system automatically operates the bi-level lighting system through its high, low and off states based on available daylight levels. The SDH operation is based on a simplified control algorithm that avoids cycling and supports simple and easy occupant adjustment of the ON and OFF set points.

This paper includes descriptions of the overall SDH strategy and system, as well as initial results from laboratory testing of a working prototype showing potential energy savings and effects on the luminous environment. Initial results show that the SDH system can significantly reduce energy and peak demand, offering 100% savings for most of the daylight hours in work spaces adjacent to windows.

The cost of the SDH system is very low, offering the potential for cost-effective commercial products that will help reduce energy and peak demand requirements in new and existing commercial buildings.

Introduction

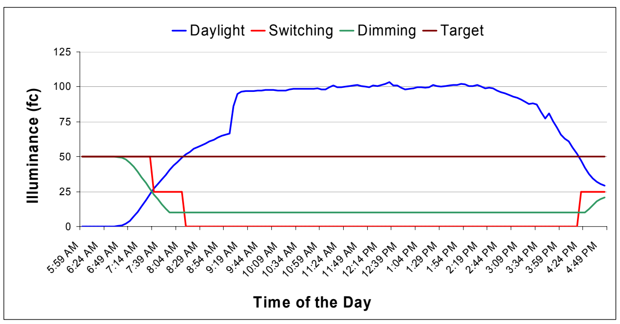
Most commercial spaces have enough daylight next to windows to eliminate the need for electric lighting. Daylight harvesting systems automatically dim or switch electric lights depending on daylight availability, offering significant energy savings. Most important they offer significant peak demand reduction, since peak demand usually occurs during the highest levels of daylight availability.

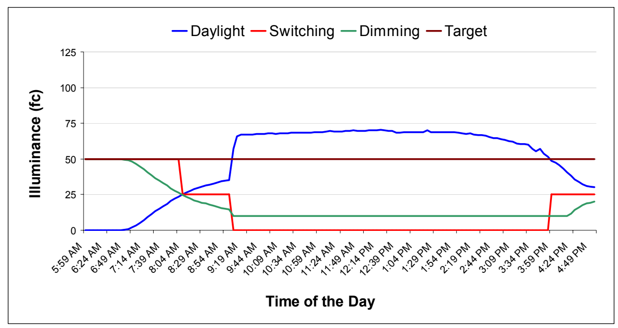
Daylight harvesting has been an active area of research for that past two decades (Rubinstein et al., 1986; Love, 1998; Cimo, 2006). While straightforward as a concept, implementation and realization of savings have been very limited. Dimming electric lighting based on available daylight is expensive, with significant equipment (dimming ballasts) and commissioning costs. To date, only a small fraction of side-lit dimming applications operate satisfactorily (Heschong Mahone Group, 2005).

While useful in low daylight areas, dimming is not really necessary in areas with high levels of daylight, where dimming is only useful during the early morning and late afternoon. Moreover, dimming ballasts are less efficient than non-dimming ballasts and consume 10%-20% power even at the lowest possible light output.

Daylight work plane illuminance measurements in a north-facing office space demonstrate that switching can be very effective in areas next to windows, which receive adequate daylight even in foggy, overcast winter days (Figure 1).

Figure 1. Simulated Optimal Switching (Red Lines) And Dimming (Green Lines) Based on Actual Daylight Work Plane Illuminance Measurements (Blue Lines) in a North-Facing Office During a Winter, Foggy, Overcast Day, Maintaining 50 fc at Distances of 4 feet (left) and 8 feet (right) from the Window Wall





While it is true that occupants might be more distracted by the dramatic changes in light levels caused by switching (as opposed to a smooth dimming function), switching will generally only occur twice a day, during early morning and late afternoon or early evening hours. Offering occupant control for the ON/OFF switching levels can greatly improve occupant acceptance.

Switching controls have been available for a long time (The Watt Stopper, 2006). While simpler and more cost effective than dimming, they are also not widely used, mainly because of commissioning costs and unreliable operation, usually due to cycling when the ON and OFF set points are not far apart in relation to the light switching steps. Even the most recently developed technologies (Cimo, 2006) require initial calibration to establish a relationship between photo sensor signal and work plane illuminance.

This paper is about a new, cost-effective Simplified Daylight Harvesting (SDH) system, which uses a very simple, robust algorithm to automatically switch lamps ON/OFF based on the signal from a control photo sensor. The SDH approach is also applicable to any single or multi-step switching control system and it works "out of the box," i.e., it does not need calibration or commissioning, eliminating the most expensive part of daylighting controls. Moreover, it supports adjustable ON and OFF set points and optional integration with occupancy sensing for improved occupant acceptance (Figure 2).

The Simplified Daylighting Harvesting (SDH) System

The basic SDH system includes a photo sensor to measure the luminance in the area of interest, a relay (or relays for bi-level control) to switch the lamp(s) ON/OFF and a microcontroller to execute the algorithm. These basic components can be configured in several potential embodiments including:

- A completely new luminaire with all of the SDH component integral to the luminaire
- A luminaire-retrofit kit in which the SDH components are integrated into an existing luminaire
- A bi-level wall switch, in which SDH components are utilized to control a space that has been wired for bi-level control.

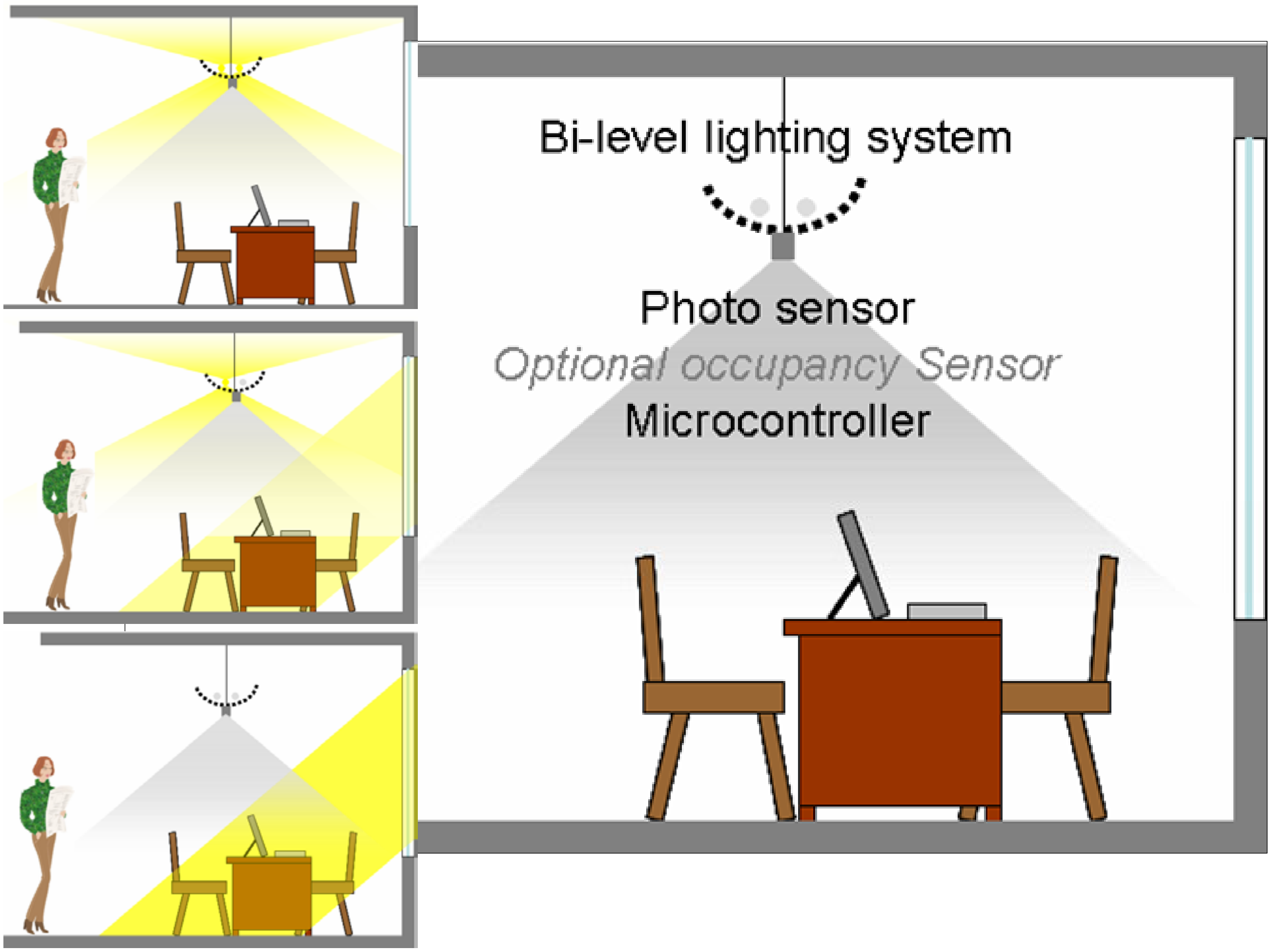
Depending on the configuration of the SDH system, the specific details of the functionality of the system will vary. Unless otherwise noted we will focus on the first configuration (new luminaire) in the paper, as it represents the most straightforward case.

In the new luminaire SDH embodiment, the photo sensor is located at the bottom-center of the luminaire and has cut off angles that match the candlepower distribution of the luminaire. The luminaire may have a single relay for simple ON/OFF control, either turning off all lamps when enough daylight is present or turning off only some of the lamps while leaving other lamps on to show that the luminaire is still functional and to provide a baseline of illumination. Alternatively, the luminaire could have multiple relays present so, even if the luminaire itself is not wired for bi-level control, the on-board relays could achieve bi-level control for daylight harvesting.

The development of the SDH system was based on addressing three main issues: reliability, occupant acceptance and cost-effectiveness.

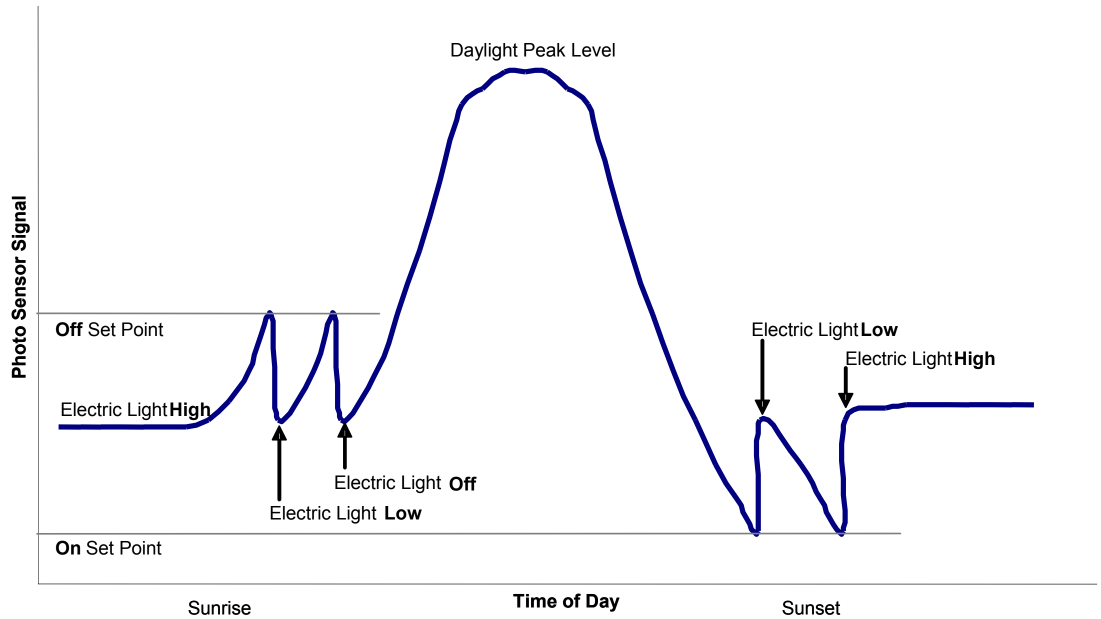
Reliability is crucial to the success of daylighting controls. The control system must function correctly under all circumstances, i.e., switch electric lights appropriately without cycling. Deviating from standard practice that relies on correlation between photo-sensor signal and work plane illuminance, the SDH control algorithm is based on the control photo sensor signal differences through the off, low and high output states of the bi-level electric lighting system (Figure 3). These differences are automatically measured every time the lights are switched through the light output states and are used to define the stepping function of the control algorithm. This continuous, automatic calibration ensures proper operation that accounts for lumen depreciation as well as changes in furniture layout and reflectance of interior surfaces.

Figure 2. Schematic of the SDH System (right) and its Operation (left) Showing High (top), Low (Middle) and Off (Bottom) States of the Electric Lighting System at Varying Levels of Daylight



To ensure proper operation under different conditions and occupant needs, the SDH control algorithm operates on adjustable ON and OFF set points in terms of a simple multiplier of the switching step between the high and low states of the electric lighting. The adjustability of the set points is synchronized through a single controller to ensure enough separation between them to avoid cycling. The algorithm is based on the electric light levels only, specifically the difference between the High and Low output that is used as the basis for an occupant adjustable step that sets the ON and OFF set points of the algorithm.

Figure 3. Schematic of the SDH Operation Control Strategy for a Bi-Level System with the Low Output State at 50% of the Full Output State



In addition to the robustness of the control algorithm the reliability of the control system depends on the appropriateness of the control photo sensor with respect to its spectral and angular sensitivity.

Occupant Acceptance

Occupant acceptance is the ultimate criterion for the success of automatic lighting control systems. Unless their operation matches the needs of the occupants, control systems are being disabled, eliminating energy and peak demand savings. While commissioning may help bring the system in an acceptable initial state, it cannot guarantee matching the occupant's specific needs for light levels, nor proper operation through time.

A critical issue regarding occupant acceptance is the distracting effect of switching (as opposed to imperceptible dimming functions timed to slowly ramp up or down). The SDH system attempts to mitigate this effect, but will ultimately need to be evaluated through field studies. These mitigation effects include:

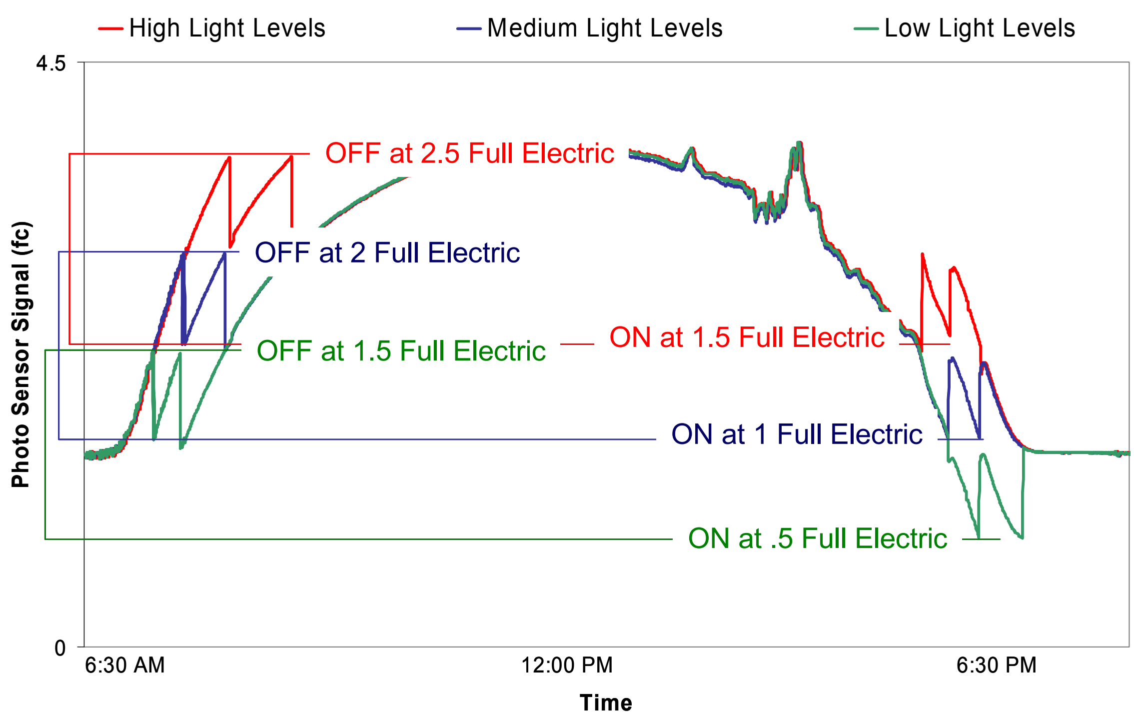
- Occupancy based switching - delaying switching until an unoccupied period
- User adjustability – user interface (fixture-mounted, wall-mounted, or wireless remote) that allows user to adjust the ON and OFF set points with a single control that maintains an appropriate dead band (Figure 4).
- Bi-level ballasts with ramping function – integration of bi-level ballasts with a ramping function for a gradual transition between high and low states.

Integration with an optional occupancy sensor offers more possibilities for customization to increase occupant acceptance, as well as opportunities for increased energy and peak demand savings. The occupancy sensor can turn lights off during unoccupied periods and only allow daylight harvesting transitions during periods of vacancy. At the initiation of an occupied period the system can turn on the lights at the level that is dictated by the photo sensor, either automatically or on occupant demand (automatic off and manual on).

Cost Effectiveness

Cost effectiveness is most important for wide spread implementation of daylighting controls. It is a function of energy savings and initial and operating costs of the control system, which can be greatly reduced through system simplicity and commission free installation and operation. The SDH system requires a very small number of components and offers the highest level of simplicity. The automatic calibration and occupant adjustability eliminate the need for commissioning, which is the most expensive part of current approaches.

Figure 4. Adjustability of ON and OFF Set Points for the Control Photo Sensor Signal Demonstrating Operation for High (Red Line), Medium (Blue Line) and Low (Green Line) Light Levels, Based on Actual Measurements of the SDH System in the Daylighting Laboratory



Most important to cost effectiveness, the SDH system has the potential to significantly reduce energy costs, especially during the high-price peak demand periods. Initial performance considerations indicate that the SDH system can save 100% of electric lighting in areas next to windows for most of the daylight hours throughout the year.

SDH Working Prototype

A working prototype of the SDH system has been developed and installed in the Daylighting Laboratory of the California Lighting Technology Center. The Daylighting Laboratory consists of two side-by-side 10'x15' north-facing office spaces with a movable separating wall allowing simultaneous measurements under different indoor conditions for comparison purposes.

The SDH prototype is installed in one of the two office spaces illuminated by an 8-foot direct/indirect suspended luminaire with two 2-32W T8 lamp banks wired in tandem. The lamp banks are controlled with relays that interface with a personal computer, which implements the control algorithm. The control photo sensor is mounted under the luminaire. It is a customized Li-cor sensor with a tube that restricts its angle of acceptance to the area illuminated by the luminaire, aiming at an ultimate closed loop approach (Figure 5).

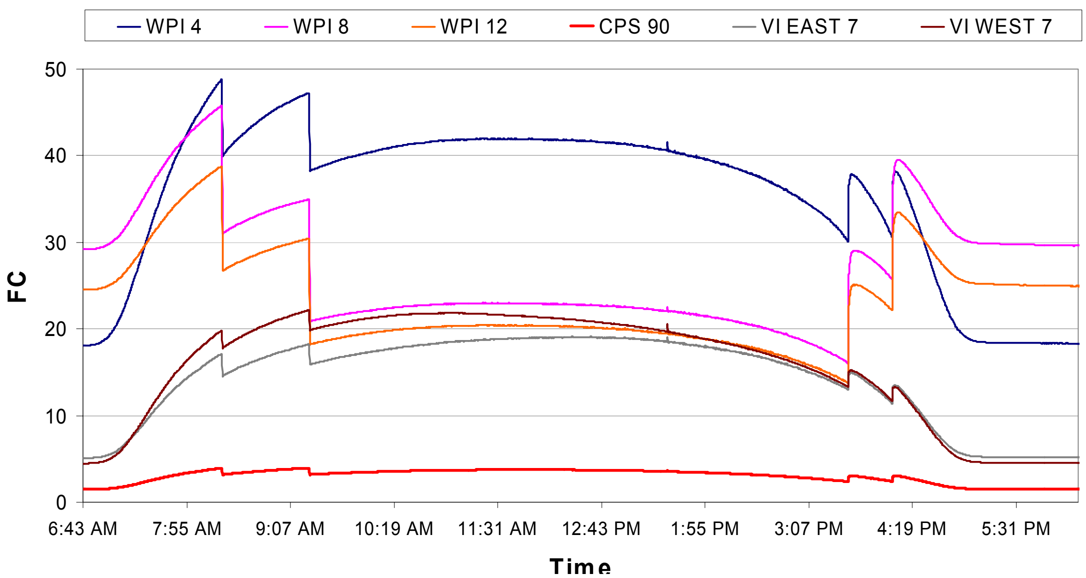
Figure 5. A Fish-Eye View of the Daylighting Laboratory of the California Lighting Technology Center, Showing the Fixture-Mounted Customized Photo Sensor of the SDH Prototype and the Various Photo Sensors Measuring Work Plane and Eye Level Vertical Illuminance Levels

The Daylighting Laboratory supports data acquisition from multiple sensors, such as illuminance, luminance and spectral power measurements. The initial measurements for the testing of the new SDH system were focused on illuminance levels at the work plane at various distances from the window, as well as at vertical illuminance at heights that correspond to the eye of a sitting occupant looking at different key directions.

SDH Prototype Performance

The performance of the SDH prototype has been very successful. The simple control algorithm has been working flawlessly under a variety of daylight conditions, such as sunny, overcast, foggy, stormy and rainy periods (Figures 6 and 7).

Figure 6. Clear Winter Day Measurements of the SDH Performance Showing the Light Levels at the Control Photo Sensor (CPS 90 on Top Plot and Blown Up in Bottom Plot) Three Horizontal Illuminance Sensors at 4 (WPI 4), 8 (WPI 8) and 12 (WPI 12) feet from the Window Wall and Vertical Illuminance Facing EAST (VI East) and West (VI West)



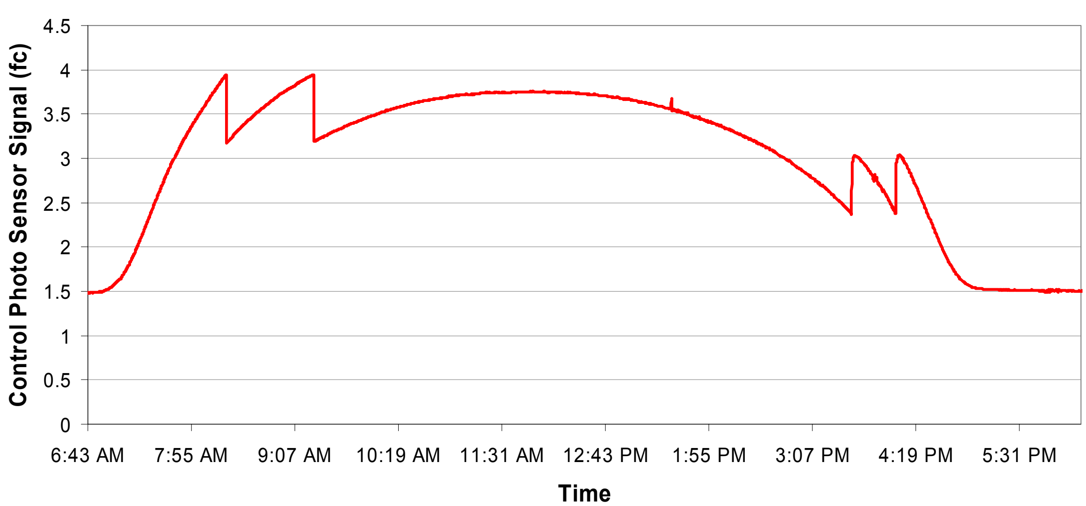
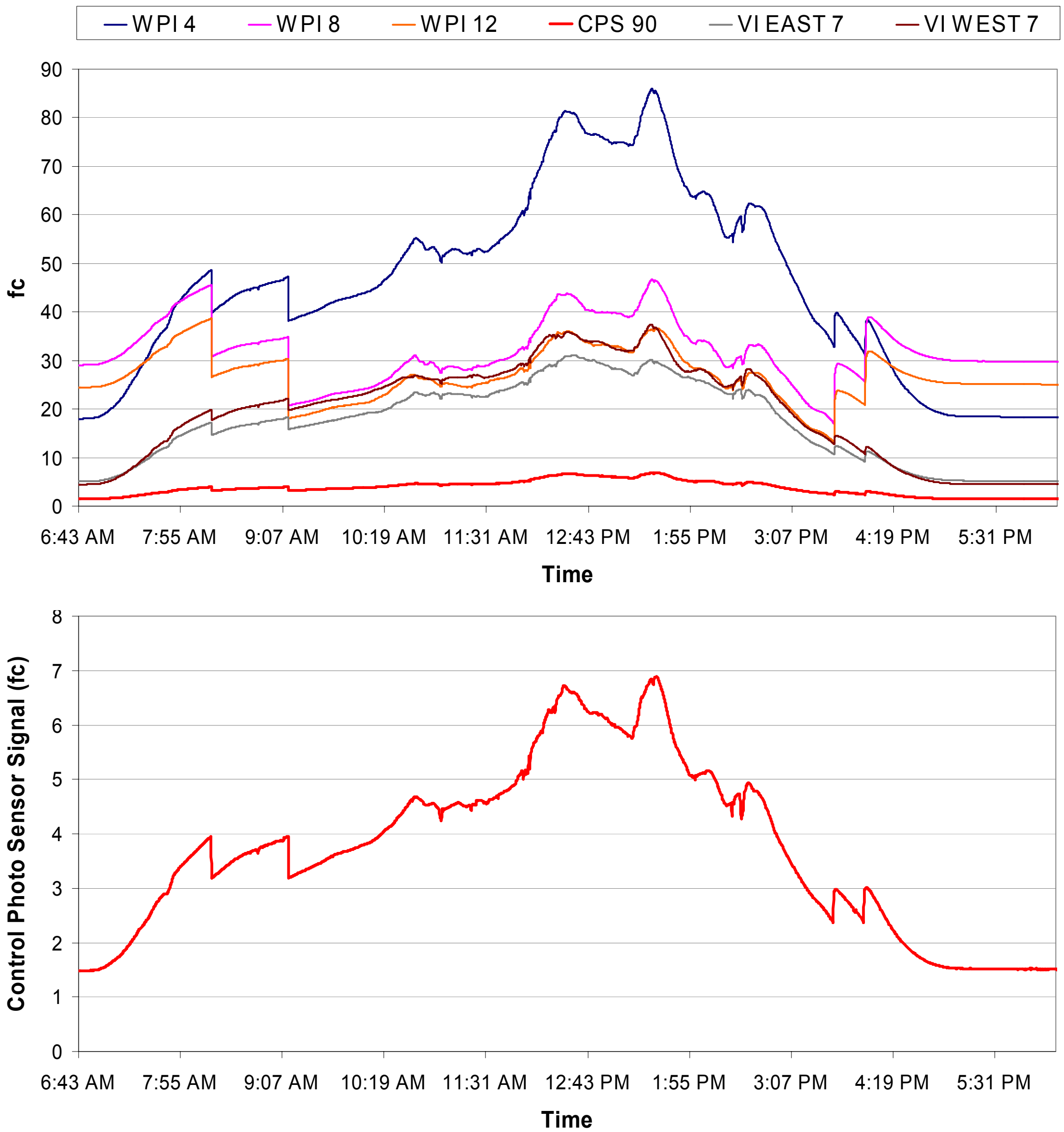


Figure 7. Cloudy Winter Day Measurements of the SDH Performance Showing the Light Levels at the Control Photo Sensor (CPS 90 on Top Plot and Blown Up in Bottom Plot) Three Horizontal Illuminance Sensors at 4 (WPI 4), 8 (WPI 8) and 12 (WPI 12) feet from the Window Wall and Vertical Illuminance Facing East (VI East) and West (VI West)



Depending on the adjustment of the ON and OFF set points, electric lights are switched to low and off maintaining desired light levels. These levels can easily be above electric lighting levels at work plane illuminance at 4-12 feet from the window wall.

The adjustment of the ON and OFF set points works as expected and the control is very intuitive, i.e., dynamically adjusting the control for higher or lower switching levels ensuring accurate adjustment without risk for cycling.

Several customized versions of the control photo sensor were explored to reduce the sensitivity of the sensor from angles directly under the lighting sensor. An optimized response was determined accounting for the angle of incidence and the distance from the floor equal sensitivity from all incoming directions.

Commercialization Potential

The SDH approach, with its simple, robust, low-cost technology has the potential for cost-effective products that will save energy and reduce peak demand in new and existing commercial buildings.

The SDH system can be implemented in various ways. The main components (microcontroller, relay, photo sensor, occupant control and optional occupancy sensor) can be housed in a single unit, or be distributed, communicating through wires or wirelessly.

Commercial products can also be produced by component manufacturers in various incarnations of the SDH system customized for specific applications, e.g., controlling groups of lamps through wired or wireless signals from single or multiple sensors. Interesting applications include an open loop approach where a single photo sensor sensing only daylight allows for customized switching of individual fixtures.

The University of California, Davis, has filed a provisional patent and has initiated outreach to the lighting industry seeking collaboration on the development of commercial products. This outreach has generated significant interest from multiple luminaire and controls manufacturers and California utilities towards the development of commercial SDH-based products.

Conclusion

Daylight levels in areas next to windows have enough daylight to eliminate the need for electric lighting for most of the day throughout the year and offer energy and peak demand savings. The Simplified Daylighting Harvesting (SDH) approach presented in this paper offers a promising, cost effective way for daylight harvesting by eliminating the need for calibration and supporting occupant control for the ON and OFF set points for increased occupant acceptance.

The key new elements of the SDH approach are:

- Automatic calibration – The Simplified Daylight Harvesting (SDH) system automatically calibrates itself upon standard installation, without need for any initial setup, i.e., it works out of the box.
- Continuous calibration – The SDH system automatically updates the switching step of the algorithm every time it switches the lighting system from High to Low. This continuous, automatic calibration accounts for lumen depreciation and changes in reflectance within the space (i.e., furniture moving, space repainted, etc.).
- Occupant controls – The SDH system supports occupant adjustment of the ON and OFF set points of the control algorithm through dynamic adjustment of the system’s response, which can be implemented in various ways, e.g., wall switch, fixture mount, or wireless infrared or RF controls.

Simplified approaches to harvesting this low hanging fruit can prove effective in reducing energy and peak demand in new and existing commercial buildings. The SDH system offers a simplified, robust, user friendly and low-cost approach with excellent potential for commercial products that will help realize energy savings from daylight harvesting.

Acknowledgements

This work was supported by the California Energy Commission through the Public Interest Energy Research (PIER) program and the University of California, Davis.

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