Overview of Smart Building Automation, Photosensor and Occupancy Sensor Technology

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1.0 Introduction

This brief technical report provides a broad overview of current Building Automation technology and "smart" systems, sensors and controls. The first section 2.0 provides an overview of Building Automation Systems and the new trend towards smart systems. The next section 3.0 provides a more in-depth overview of photosensor technology and the last section 4.0 provides an overview of occupancy sensor technology.

2.0 Building Automation Systems

Our electrical systems inside and outside of buildings have been developing from systems of "dumb" wire connected devices where the functionality often had to be designed and configured ahead of time to "smart" wired and wireless devices that are addressable, intelligent and can communicate via the internet allowing global access for control and monitoring. Not only are building electrical systems seeing these developments, the US Department of Energy and electric utilities around the country are working on the idea of a smart electrical grid for our cities that rather than must providing one-way power has two-way communication, can monitor and modulate end use, and has built-in intelligence to detect faults and make intelligent reactions.

Building Management or Building Automation Systems (BAS) are the automated centralized control of a building's HVAC, lighting and other systems. Building's controlled by a BAS are often referred to as "smart buildings" although new developments have improved drastically upon the "smartness" of these systems by going digital and adding in addressability and built-in diagnostics, intelligence, and communication.

Today, "smart" systems refer to this new world of digital devices, coined the "Internet of Things", that are able to collect, interpret and exchange data. This is anything from toasters that can be controlled remotely to a smart fridge, smart lights, smart thermostats, smart security systems, smart doorbells, etc…

2.1 Addressability

One of the first movement towards "smart devices" in the lighting industry was to allow for more flexible lighting control and to reduce expensive wiring by using daisy-chained data connections between switches and devices separate from the actual power wiring. The Digital Addressable Lighting Interface (DALI) protocol was one of the first and popular protocols to come about to allow for this control network addressability (http://www.dali-ag.org/)

Each switch, sensor, or luminaire in a DALI system would have some built-in communication circuitry to have its own digital 'address'. This type of control network leads to ultimate flexibility in the control of lighting fixtures: the control can be remotely accessed, switches and sensors control can be mixed and matched with the various luminaires on the system, control can be easily programmed and overridden, and it can all be done separately from the power wiring.

2.2 Internet of Things (Intelligence and Communication)

More recently, "smart" systems have moved beyond just simple addressability and now include built-in processors that can collect and exchange data globally via the internet and can interpret the data and respond accordingly. This new world of smart devices is often coined the Internet of Things (IoT). This growing network of smart devices is evident as they recently made the news as playing a role in a hacking attack – one that took advantage of all these smart internet-connected devices to bombard internet servers with fake request and nearly shutting down several major websites over a day or so.

On the energy side, the idea of a “smart” grid and “smart” appliances has a lot of potential benefits. Particularly when larger appliances, HVAC equipment, EV car charging, battery storage and/or PV production are part of the system there is tremendous potential for significant energy savings and even more significant demand capacity savings. The National Renewable Energy Laboratory (NREL) has recently dedicated a new facility, the Energy Systems Integration Facility (ESIF - http://www.nrel.gov/esif/) largely to the development and research of smart power grids and associated smart appliances, storage, power production and other devices that could be part of the overall system.

On the user experience side, the idea of “smart” homes where you are able to monitor and control the various devices in your life from your car, to security systems, doorbells, thermostats, lights, and toasters, via the smart phone that we all carry in our pockets is very intriguing. With GPS and motion technology, the potential to automate this remote control is also very intriguing: lights and thermostat adjusting to your preferences automatically simply when you walk into a room, or even averaging a room full of people preferences to appease the most occupants.

2.3 Smart Building Components

Going forward there may be two main groups of smart building technologies in the industry: those that are **building integrated** and just part of the building’s BAS and electrical, lighting and HVAC systems and those that are **end-use consumer products** that can be plugged in to existing power infrastructure and programmed to be controlled wirelessly.

Examples of building integrated smart products include:

- Manual switches that are addressable and with integrated sensors that not only provide manual on/off control but can be programmed to control any other end use on the system and to automatically turn on/off based on occupancy. (Wattstopper and others)
- Light fixtures that are addressable and have integrated occupancy sensor and wireless mesh technology that can be programmed to be controlled by any switch/sensor on the system.
- Smart Relays that can be used to monitor and control larger loads and/or entire circuits.
- Addressable and adjustable sensors: photosensors, occupancy sensors, and thermostats, that can be mixed and matched with the various loads and equipment on the system
- Electrical outlets tied to occupancy sensors to turn off “phantom” loads when not needed.
- Battery Backup and Demand Saving systems that use large battery banks to smooth out electrical demand and to provide back-up emergency power.
- Security cameras that are accessible remotely via the internet and can be integrated with the front door bell or occupancy sensors.

Examples of consumer end-use smart products include:

- Tacked on home monitoring and control. Products like Samsung’s “Smart Things” that can be added to a variety of existing electrical products, like a toaster or alarm clock for example, and be monitored and controlled remotely. More and more electrical products will likely have this wireless connectivity built-in.

- Tacked on lighting systems like Philips Hue, a line of wireless light sources and associated controls that allow lighting to have internet accessibility and be remotely controlled, scheduled and so forth.
- Thermostats like Google's NEST product that is internet accessible and has some built-in algorithms meant to learn your schedule and temperature preferences and adjust the control accordingly. This is not unique to NEST, many more advanced home furnace systems have similar controllers but NEST is an consumer product that can be added to most other systems.
- Both Electric Vehicles (EVs) and EV Charging Stations are becoming smart in that they are connected to the internet and many can be monitored and controlled remotely. EV Charging stations also offer an interesting battery storage opportunity for reducing demand.

2.4 Smart System Communication Protocols

There are a number of communication and data protocols used among Building automation and control systems. A quick search on Wikipedia indicates 20+ protocols out there. The following are some of the more prevalent and popular protocols used in common systems today.

- BACnet – popular ASHRAE, ANSI, and ISO standard protocol designed by an ASHRAE committee for building automation. One of the more common protocols in BAS systems.
- DALI – The Digitally Addressable Lighting Interface is an open IEC standard developed to allow for communication between different lighting equipment.
- EnOcean – Consortium of energy harvesting wireless technology with an ISO/IEC wireless communication standard. The attractive thing about this approach is the self-powered nature of the system's sensors and switches. Self-powered devices open up a new market of truly wireless, layered on, control systems that are not limited by access to power.
- KNX – another popular EN and ISO standard protocol for Building automation.
- LonTalk – an ISO protocol optimized for control and networking devices over power or fiber optic wiring. Along with BACnet one of the more popular BAS system protocols in use but more proprietary as it's developed and maintained by the Echelon Corporation
- Zigby – is an IEEE suite of protocols used to create personal area networks with small, low-power digital radios. Intended to be simpler and less expensive that other protocols such as Bluetooth or Wi-Fi. Popular protocol used to establish mesh networks to get wider coverage with less expense.
- Bluetooth – a wireless technology standard for exchanging data over short distances very popular with the rise of smart phones and Bluetooth enabled radios and other electronic devices.

2.5 Future of industry

Current trends seem to indicate that we will only see more and more "smart" devices. With this, there will likely be a need for more accurate and / or less expensive sensor technology and wireless control system technology. The next two sections go into more detail into common building sensor technologies and offer future development recommendations.

3.0 Photosensors

Photosensors are used in the Building Automation systems to adjust the light output of a lighting system based on the amount of light sensed. To date, these sensors have been largely uncalibrated and field adjustments are required to only partially calibrate to the application. In 2007, the Lighting Research Center (LRC) completed research into the actual performance of these systems resulting in a great resource for more in-depth information on photosensor systems and their performance characteristics. The sections below largely summarize information in this report.

A quick definition first – a "photosensor" is the overall system that includes a "photocell" (the light-responding circuit and housing) and a "controller" (a small purpose-built computer that controls the lighting).

3.1 Photocell Types

There are two types of photocells typically used in building automation control systems: photodiodes (typically silicon) and photoconductive cells (typically cadmium sulfide – CdS).

- Silicon photodiodes produce a small current with good linearity to the number of photons striking the cell, and that is stable over time and temperature. They typically include filters to make the spectral response approximate the human eye.
- CdS photoconductive cells have a variable resistance that lowers under increasing light levels, however the relationship is not linear and the cells are not as stable. The cells have a memory effect where the sensitivity changes depending on past light exposure and temperatures. The CdS cells have a spectral response similar to the human eye and so no filter is needed. This and their ability to withstand higher voltage keep them inexpensive and hence useful for simple lighting circuits.

Most photocells are mainly concerned about detecting changes in light and do not take the expensive to design the housing and calibrate to read absolute light levels or calibrated illuminance. Companies like Li-Cor will offer calibrated photocells (typically silicon photodiodes) that do accurately read illuminance for applications where this accuracy may be needed such as open-loop lighting control systems.

3.2 Photocell Spatial Sensitivity

One key characteristic impacting the performance of the photosensor control system is how sensitive the photocell is to incident light from different directions. The term illuminance is used to describe the amount of light striking a planar surface from all directions. Specifically, it is the lumens per area (often lumens per sf or footcandle) that is striking a surface. Due to physics, the intensity of photons on the surface follows a cosine law relative to the angle of incident light – a cosine or Lambertian sensitivity. Figure 3-1 shows the spatial sensitivity of an example photocell product compared to this cosine sensitivity which defines the illuminance at a point.

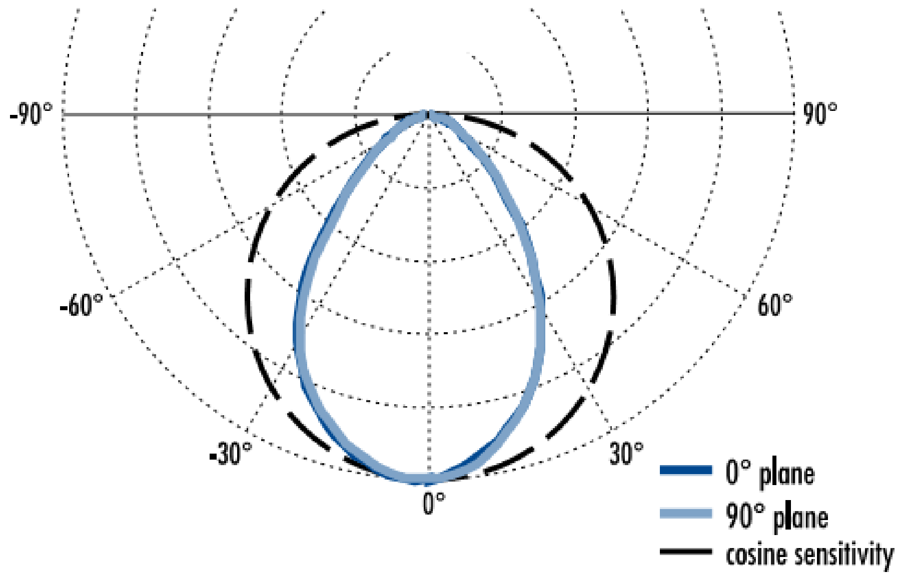

Figure 3-1: Photocell spatial sensitivity: example photocell vs illuminance (cosine)

This is an important distinction in that unless a photocell's spatial sensitivity is calibrated to a cosine sensitivity, the photocell is not an accurate illuminance meter. It can be calibrated to match illuminance under a given, static, lighting condition, but as soon as that lighting condition changes it no longer accurately reads illuminance.

Many current manufacturers erroneously discuss the signals they get from their sensors and the corresponding set-points in terms of illuminance – which can be very misleading and misinforming for designers trying to simulate daylighting conditions.

Ultimately, perfect cosine sensitivity is not needed but it is important to understand the spatial sensitivity of the sensor and have the data to properly locate and simulate the performance. For example, a shielded photosensor, with a sharp cut-off in the spatial sensitivity, could be useful for controlling exterior shading particularly given that the shielding matches the shading on the given windows being controlled.

3.3 Photocell Spectral Sensitivity

Another key characteristic of a photocell is sensitivity across the spectrum of incident radiation. Illuminance is defined by a human spectral response function or the CIE photopic V-lambda curve, see the solid line in Figure 3-2. While most photosensor manufacturers either use filters or CdS photocells (as discussed) to more closely match the photopic curve, photosensors without any correction would have strongest sensitivity in the non-visible infrared range, the dotted line in the graph. This type of sensor could potentially falsely trigger in the dark with a radiator heating system turning on.

For most building applications controlling electric lighting, it is best for the spectral sensitivity of a sensor to closely match that of human vision, the photopic v-lambda curve. Interior lighting, while appearing white, is often a mix of distinct wavelength spikes across the visible spectrum. If a sensor, like the filtered silicon diode represented by the dashed line below, reads one of these wavelengths, say a 500nm spike off by 300% (.25 to .75), the overall reading would be off when compared to the reading under daylight which is completely full spectrum.

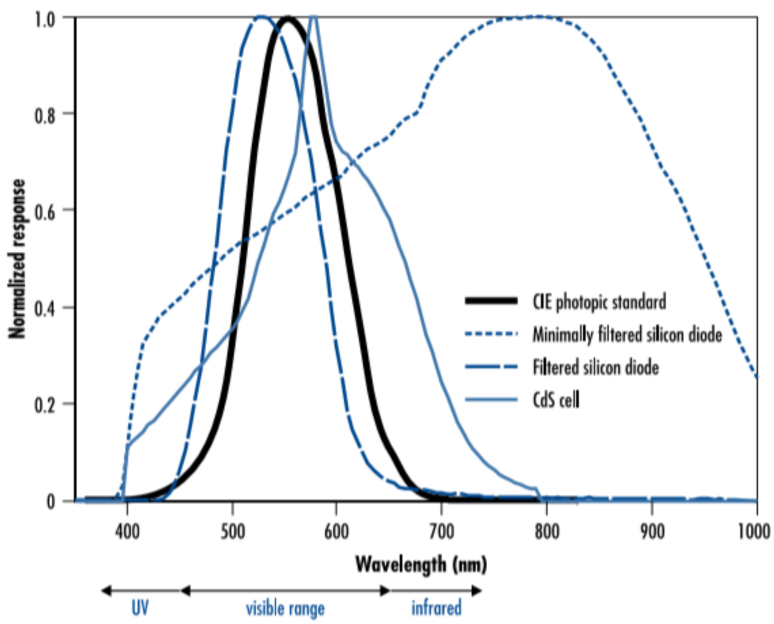

Figure 3-2: Photocell spatial sensitivity: example photocell vs illuminance (cosine)

3.4 Controller Algorithm Types

The light level from the photocell is an input into the system's controller which then determines what to do with the luminaire light levels with control voltage output: 0-10v for dimming systems, and binary (on/off) for switching systems. There are two main algorithm types that are largely a function of the photocell placement:

- Open loop systems typically have the sensor located outside, or looking directly out a window or directly up into a skylight, and have no, or very little "feedback" or signal from the lights they are directly controlling. They systems are sometimes misused with interior sensors receiving too much direct feedback, which essentially lowers the full light-output potential of such a system.
- Closed loop systems are typically interior sensors and allow for feedback from the lights they are controlling in their control algorithm. These control algorithms are necessary for most any interior photosensor application.

In addition to open and closed loop, there two main dimming algorithms and both on/off and multi-step algorithms that are used:

- Constant Set-point (integral control) algorithms only have one set-point and work to maintain that set-point at all times by dimming the electric lighting at the same rate the daylight is increasing relative to the senor signal. If the signal is below that set-point, the lights are on at 100% and if it is above the lights are off. This can work well when the daylight and electric light behave in the same in the space, which is not typical in most daylit spaces.
- Sliding Set-point (proportional control) algorithms have two set-points, one at which the lights will begin to dim and one where they will be at their lowest level. This can often serve daylit spaces better as the lower setpoint can be set under electric lighting conditions only and the higher setpoint can be set under the different daylighting

conditions. However, it can be challenging in ensuring the daylighting signal, relative to the workplane illuminance, is higher than the electric ratio and in finding the exact daylight conditions to set the upper set-point.

- On/Off and Multi-level algorithms work similarly and need either a set-point and a bandwidth or a high and a low set-point so that there is a deadband between the on and off signals. Otherwise, particularly in closed-loop situations, flicker will occur in the system.

Figure 3-3 shows typical response functions for these common control algorithms.

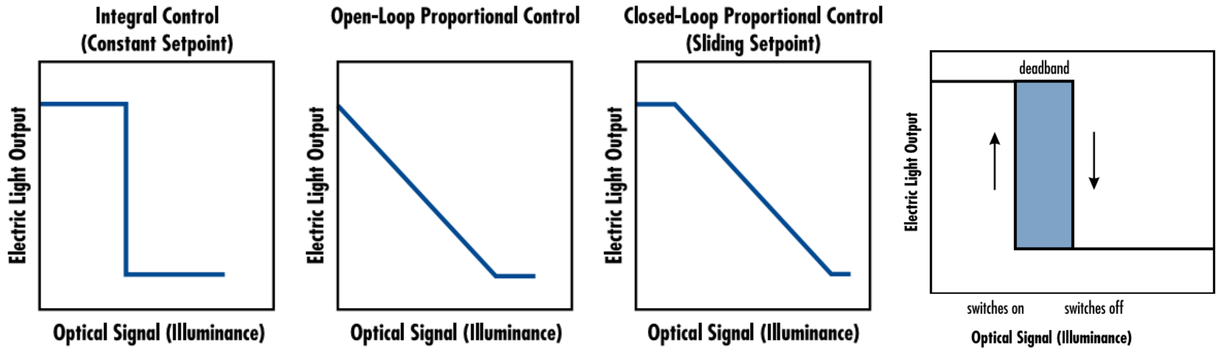

Figure 3-3: Archetypical response functions for dimming (3 left) and switching (1 right) photosensors

3.5 Overall range and resolution

The range of a photosensor system is typically limited on the low end by the amount of noise that reduces resolution and on the high end by either exceeding a 10V control signal or saturating the photocell. The overall range needed for daylighting applications is likely not possible with a single photocell, but could easily be adjusted with different transmittance filters for different models.

Typical daylighting applications will range from placing sensors in darker interior locations where the sensor has to be more sensitive to small changes in light to exterior locations where it needs to be able to read high light levels but does not need to be extremely sensitive. Two (high and low) to four (high, medium, low, nighttime) options would likely be adequate for the range of applications. The four levels may be something like:

- High: 500 – 10,000 fc – used for exterior applications when controlling interior or exterior fabric shades, or interior lighting with open loop control
- Medium: 50 – 2,000fc – used for brightly lit interiors or for locations looking directly out a window
- Low: 0.5 – 100fc – used for daylit interiors and locations that have a low overall brightness but vary linearly with light levels.
- Nighttime .1 – 10fc – used for exterior lighting and simply needs to determine when it becomes night, when light drops below 2fc or so. These could likely be cheaper circuitry and the spatial and spectral sensitivity is not critical.

3.6 Photosensor Location and System Simulation

Given the complexities of accurately measuring and controlling light discussed above, the actual photocell placement and in-situ system settings are equally important in achieving optimal energy savings from such systems. Bad placement and settings can negate the control algorithm being used and eliminate any potential energy savings. Figure 3-4 below illustrates how different a sensors electric lighting / daylighting signal ratio can be even in a simple side-lit square space. On the left, the sensor gets some signal directly from the electric lighting but lots of signal from the ambient daylight and electric light reflecting of the rooms surfaces. In the middle, the sensor is dominated by an electric lighting signal and on the right, it is dominated by a daylighting signal. Since the system is supposed to turn down the electric lighting in response to incoming daylighting it is essential that this relationship is known and addressed in the systems control algorithm. Too often in practice this is not done leaving the installed photosensor control system saving minimal to no energy.

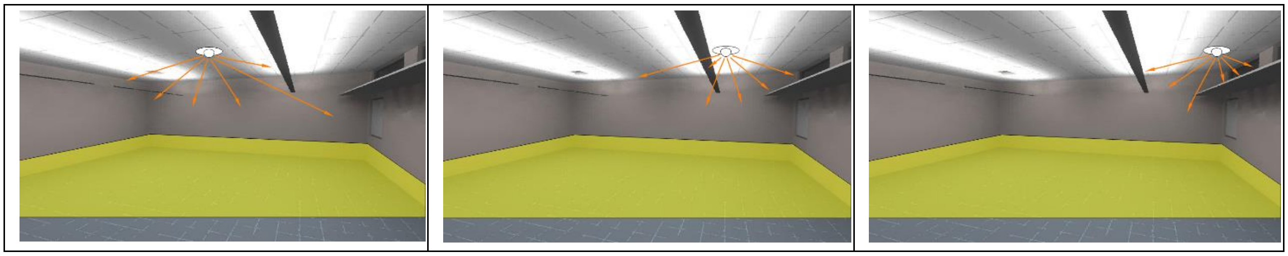

Figure 3-4: Variable relationship between electric lighting and daylighting sensor signals

The Sensor Placement + Optimization Tool (SPOT Pro) is a computer software aimed at bridging this gap between electric lighting and daylighting with simulation tools to determine optimal control scenarios. SPOT takes into account photosensor spatial sensitivity and simulates daylight and electric lighting conditions throughout the year to determine optimal photosensor placement for a given application and to determine a sensors electric light vs daylighting ratios to determine an optimal control algorithm. Figure 3-5 illustrates some screen shots from SPOT illustrating the determined optimal location for sensors in a classroom.

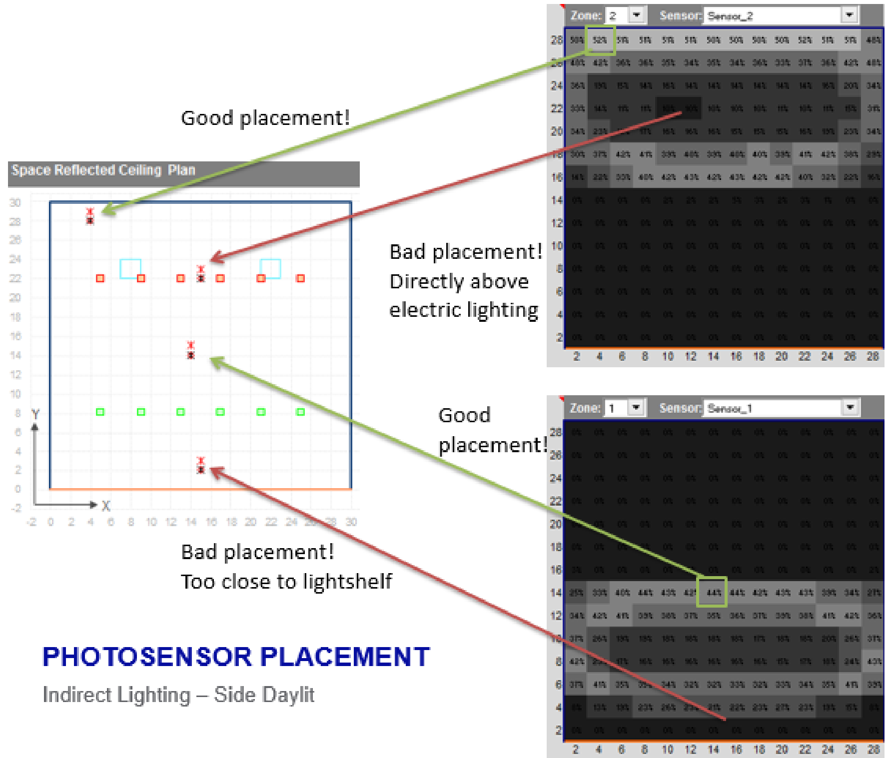

Figure 3-5: Variable relationship between electric lighting and daylighting sensor signals

SPOT helps determine the optimal locations automatically and then allows the user to play with system set-points to see how the system will perform throughout the year and to identify any worst-case problematic conditions. The following illustrate system setting analysis for both a good and bad sensor location, the placement and resulting settings alone took this system from maintaining a 40fc minimum at all times to dropping below 20fc at times.

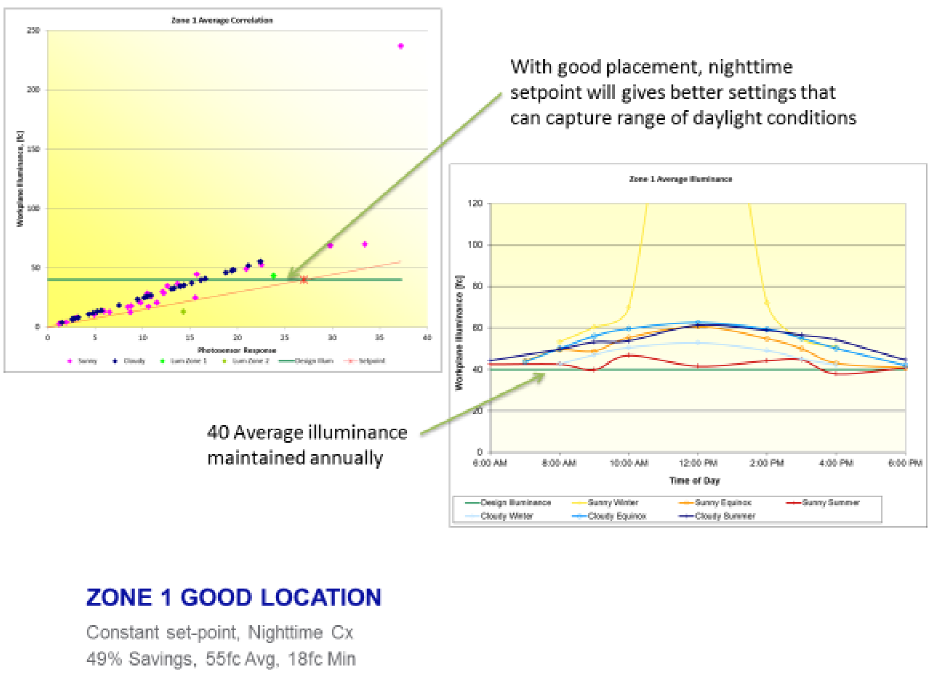

Figure 3-6: Best control for a well located photosensor

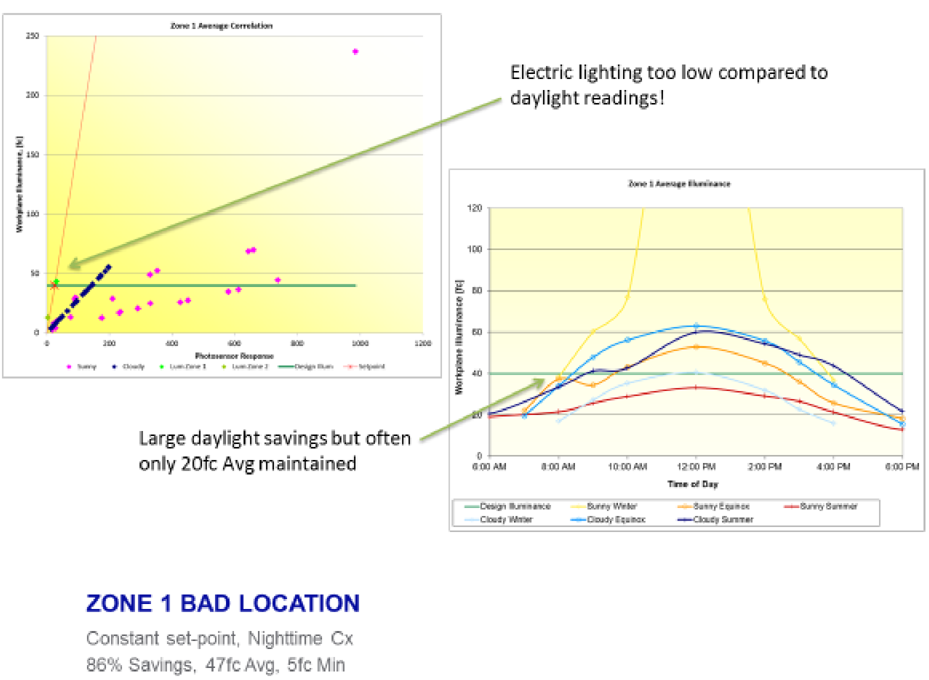

Figure 3-7: Best control for a poorly located photosensor

3.7 Current Manufacturers

The 2007 LRC report provided a good summary of most current photosensor manufacturers, that are repeated in Table 1 below. Since, some of the companies and systems have come and gone, merged or changed names but the photosensor system technology is largely the same. Some photosensor system manufacturers appear to use photocells from other manufacturers, namely Novitas seems to OEM their sensors for use in other products. Wattstopper and Douglas Lighting Controls are two of the more popular dedicated lighting control companies that compete with the large lighting company offerings like Lithonia or Acuity (was Sensor Switch).

Table 1: Photosensor manufacturers test in 2007 LRC Photosensors specifiers report

Manufacturer	Model (Controller)	Sensor	Type	Sensor Type	Control Type	# of Zones	Ballast Compatibility	Indicators
Axis Technologies	AX232B-120	Included w/control	Dimming	CdS	Logarithmic proportional *	1	Axis	None
Douglas Lighting Controls	WPC-5621	Included w/control	Switching	Si, light to frequency	Switching	1	Any	Two LEDs show on/off states and blink when within deadband
Douglas Lighting Controls	WPC-5700	Included w/control	Dimming	Si	Integral	1	0-10 V	None
Easylite	2500072 Daylite Harvester	Included w/control	Dimming	Si, integrated amp	Closed-loop stepwise proportional	One; multiple with additional hardware	Easylite	Flashing fluorescent lamps
Leviton	CN100 and CN221	ODCOP-W	Dimming	Si	Integral	1	0-10 V	Eight LEDs indicate mode, status, and light level
Lithonia - Acuity Brands	ISD DPC (ESD-PLC)	Included w/control	Dimming	Si	Integral	1	0-10 V	None
Lithonia - Acuity Brands	Digital Equinox, SYRS EXT	LSA APS IN R2	Dimming	Si	Integral	1	0-10 V	LEDs blink status code
Lutron	ECO System	C-SR-M1-WH	Dimming	Si	Closed-loop proportional **	At least 64 (individual ballast groupings)	Lutron	Alpha-numeric and graphical display on PDA remote
Novitas	02-PCC	01-PCI (indoor)	Switching	CdS	Switching	1	Any	Two LEDs show whether photocell signal is above or below setpoints
PLC-Multipoint	LCM-12	CES	Switching	Si	Switching	4	Any	4-line alpha-numeric LCD
Sensor Switch	CM-PC-ADC ***	Included w/control	Dimming	CdS	Integral	1	0-10 V	One LED blinks different patterns
			Switching		Switching		Any	
Watt Stopper	LCD-203	LS-290C	Dimming	Si	Proportional	3	0-10 V	2-line alpha-numeric LCD
Watt Stopper	LCO-203	LS290-C	Switching	Si	Switching	3	Any	2-line alpha-numeric LCD
Watt Stopper	LS-301	Included w/control	Dimming	Si	Closed-loop proportional	1	0-10 V	Two LEDs inside photosensor indicate communication, errors

3.8 Future Product Potential

Some ideas for future photosensor products:

- Customized LightLouver photosensor. LightLouver is a side-daylighting louver product with a known and fixed light output to exterior vertical input signal relationship. A photocell optic that could match this relationship could provide easy open-loop control for an entire façade of spaces with LightLouver. LightLouver is interested in discussing this more. (www.lightlouver.com)

- A wireless, self-powered and addressable sensor that can be used in retrofit applications, placed wherever necessary with no power or control wiring needed, and able to self-power and provide signal input to a control system.
- Photosensors that have illuminance or other known (predictable) readings such that true annual open loop calibration is possible.
- Image based sensors that use digital camera technology to not just capture the amount of light but the spatial distribution of such light. These could be used to read a sky image and make predictive/proactive control decisions, or used in a space to various zones of light levels.

4.0 Occupancy Sensors

Occupancy sensor systems are common in Building Automation to turn on/off lighting or other unnecessary electrical loads in a given space when it is occupied/unoccupied.

4.1 Passive Infrared (PIR) Sensors

Passive infrared technology detects heat emitted from a human body in motion and rely on a clear line of sight, see the example coverage patterns in Figure 4-1 for a family of WattStopper occupancy sensors.

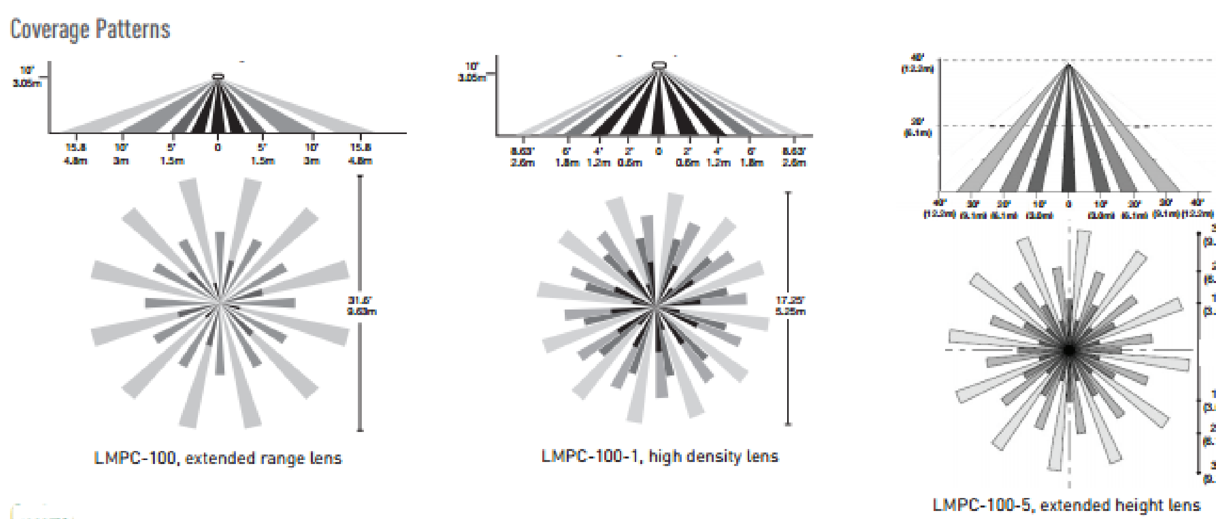

Figure 4-1: PIR Occupancy Sensor Example Coverage Patterns

The coverage of these types of sensors is typically circular, centered at the sensor with various radius and height coverages available. The cover is provided via fingers or lines of PIR detection. In order to detect motion, a warm body has to cross these fingers of detection. Hence, a person sitting in a room, typing at a computer with very little major motion, could not trigger this type of occupancy sensor and allow the lights to turn off. Getting out of your seat would likely trigger them back on in an occupancy sensing scenario but still an event that would be best to avoid. These sensors can also be triggered by hot air if too close to an air diffuser.

These sensors can work very well for enclosed spaces, high ceiling areas or areas with direct line-of-sight viewing, and spaces where it may be necessary to mask unwanted detection in certain areas.

4.2 Ultrasonic Sensors

Ultrasonic technology detects occupant movement within a room and have the ability to detect movement around partitions. These sensors will send out ultrasonic sound waves into the room and measure the time and frequency of their return. These sensors have a limited distance in which they can detect minor motion and major motion, see the example coverage for an ultrasonic photosensor in Figure 4-2.

Changes to the returning waves indicate motion and occupancy in the room. While these sensors are good at picking up any motion in a room even behind obstacles, they can falsely trigger in high ceiling spaces or spaces with high levels of vibration or air flow.

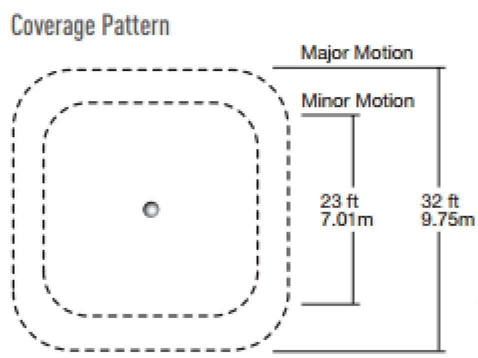

Figure 4-2: PIR Occupancy Sensor Example Coverage Patterns

4.3 Dual-Tech Sensors

Most manufacturers also offer dual technology occupancy sensors, using both PIR and Ultrasonic sensors with algorithms to require both or either to turn on and off the systems. Often they are set up to require both PIR and Ultrasonic detection to turn on, but only on or the other to stay on. This approach can provide the best occupancy detection and limits false-on and false-off situations.

4.4 Control Logic

Occupancy sensor output has to be tied into a controller to then determine what to do with the connected loads. These controllers typically have similar simple logic:

- Occupancy vs vacancy logic: "Occupancy" logic will turn on whatever load as soon as occupancy is detected and turns it off when occupancy goes away. "Vacancy" logic allows for manual on and only turns off the load when occupancy goes away. This is a nice algorithm to use in many smaller, individual spaces as it allows the user to decide if they want the load (typically lights) turned on in the first place. Often, if a space is only briefly occupied or there is adequate daylight in the space, occupants will choose to keep lights off on their own. For larger public or open office spaces occupancy sensors are a better fit as occupants tend to not have control or feel responsible for general lighting.

- Time delays are a necessary and common feature to occupancy sensor control systems to avoid false offs when a space gets still or silent. Typically time delays of a couple minutes up to 30 minutes are used to avoid false offs.

4.5 Fixture and Switch Integrated

Many manufacturers are starting to integrate occupancy sensors directly into wall switches and lighting fixtures for localized occupancy control. This can be nice for small applications where a central control system does not exist and would be too costly. However, for projects with a central control system that can be overkill and not integrate well with the rest of the system. Additionally, for lighting control it is often more aesthetically pleasing to control (dim or turn-off) all lights in a space or zone together rather than allow each one to turn off or dim on its own control, which leads occupants to often think something is broken.

Switch integrated occupancy sensors are a nice easy technology for local occupancy control and are usually setup as vacancy sensors which works very well for smaller spaces. One common complaint about these switch integrated sensors, the occupancy lens looks too much like a button and always gets dented in, as seen in Figure 4-3. A different lens or housing design could likely mitigate this issue.

Figure 4-3: Wall Switch Integrated Occupancy Sensor Failure: Lens mistaken as button

4.6 Future Products

Some ideas for future occupancy and thermal sensor products:

- A combined Passive Infrared and Mean Radiant Temperature (MRT) thermal sensor? Most thermostats measure the air temperature to determine comfort and adjust HVAC systems accordingly. However, MRT more closely matches comfort that humans feel and could lead to more accurate and energy saving HVAC control sytems.
- Like an image-based photosensor or weather detector, an image-based occupancy detection sensor could be made that would detect changes across an image and could even be zoned to control several loads based on the one sensor input.