Developing a new type of photosensor with variable field of view

L. T. Doulos[1]*, A. Tsangrassoulis[2], F. V. Topalis[1]

[1] Lighting lab., National Technical University of Athens, Iroon Politechniou 9, 157 80 Zografou, Tel +30 210 772 3627, Fax +30 210 772 3628, fvt@central.ntua.gr, ldoulos@mail.ntua.gr

[2] Dept. of Architecture, University of Thessaly, Pedion Areos, 383 34 Volos, atsagras@uth.gr

Abstract

Harvesting daylight can be considered as a very important strategy in reducing artificial lighting consumption in buildings. Nevertheless, daylight responsive systems are widely misunderstood and they have been characterized hastily as problematic. The lack of knowledge concerning operational details of these systems has constituted a serious impediment to their widespread use and a lost opportunity for achieving substantial energy savings. In addition to that and taking into account the increased number of manufacturers there isn't any process of developing technical standards. For practical reasons photosensors are located on the ceiling minimizing interference from activities in the room but complicating their control and commissioning. The correlation of the lighting levels between the working plane and the ceiling, which is a crucial parameter during commissioning, is strongly depended on the position of the photosensor and its spatial response. The present paper proposes a photosensor with variable field of view (FOV) through the use of a telescopic cylinder. Adjusting the field of view, the ratio of the ceiling to workplane lighting levels is affected together with energy savings and lighting adequacy. In order to examine all the above mentioned effects, a number of experiments were performed using a scaled room (1:10). Both, photosensor and illuminance values on the working plane were monitored on an hourly basis for various FOVs and sensor positions. The ability to adjust FOV allows lighting designers to predefine sensor placement and FOV using simulation analysis.

Keywords: Daylight, Field of view, Position of the photosensor, Photosensor

1. Introduction

Exploiting daylighting can significantly save energy use especially in office buildings. Although there are many case studies [1-15] documenting the energy benefits of lighting control with photosensors, building contractors are rather reluctant to install such systems not only due to the increased cost but also to their hypothetical unreliability in achieving predicted energy savings. The key component is the photosensor, the behaviour of which defines the whole system's efficiency. Consequently, for an optimum planning of a daylight responsive system not only is the selection of the most energy efficient components [15] required but also accurate computations of daylight at sensor's level and position are needed which in turn will affect the commissioning procedures [16].

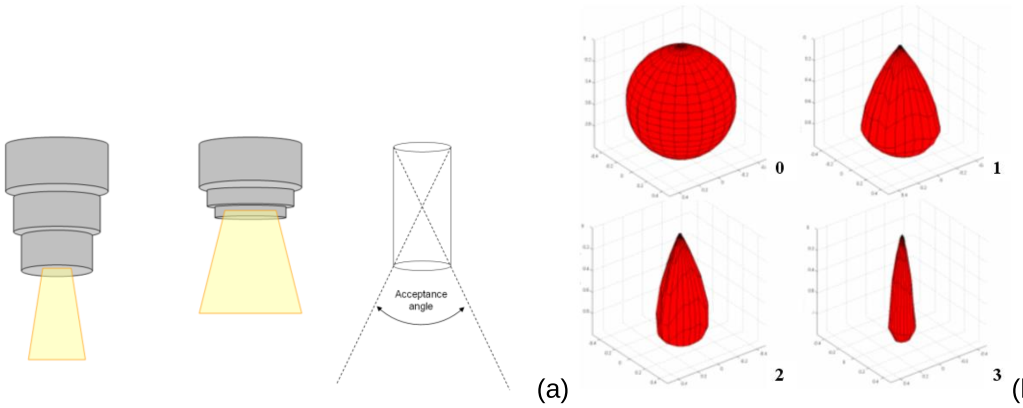
Placement of the sensor with regard to its spatial response has received attention by Mistrick et al [9]. Based on the results of Rubinstein et al [8], they simulated three types of photosensors with complete, partial and no cover in their FOV. The most suitable position of the sensor is in direct relation to the stability of the ratio of ceiling/workplace illuminance for all possible climatic conditions. Mistrick and Sarkar [11] extended the above research applying simulation analysis in larger spaces (five classrooms) using the same criterion, in an effort to define the proper placement of the sensor. However, the previously mentioned ratio should not be considered as the only criterion since energy savings and lighting adequacy can vary

[1] * Corresponding author

considerably for different positions and spatial responses of the sensor ,although the illuminance ratio is the same [17].
Recently, there has been an effort to embody new technologies by developing photosensors using CCD cameras or CMOS image sensors instead of photodiodes [18-21]. These sensors are quite promising, in the sense that they can measure luminance patterns [22] as the human visual system and they can replace multiple sensor systems. However, their capabilities are rather limited. There are errors associated with the estimation of luminance from a scene image when deriving illuminance from luminance and during the calibration procedure and commissioning [19]. Except for these, their increased cost and size can impose practical limitations during installation. A conventional photosensor using a simple constant set point control algorithm (integral reset algorithm) can perform equally well with a CMOS sensor [21].
According to the above, development of a sensor with variable FOV is necessary especially during the commissioning procedure. The concept is to use a small telescopic cylinder. Adjusting the length of the cylinder, the angle of light acceptance is modified. Consequently, selecting the proper FOV in relation to the sensor’s position, the illuminance ceiling/workplace ratio can remain relatively constant during the operation schedule of the space improving system’s performance [8]. The experiments with the new photosensor were performed inside a scaled room (1:10) located in an open, unobstructed place.

2. Development of the new photosensor

The performance and the energy savings of a daylight responsive system are strongly affected by the FOV and the position of the sensor. The ideal placement of a sensor is, of course, on the working plane itself. However, this position is not practical since it would likely be disturbed or shaded by interior activities. The variation in light distribution throughout the room, caused mainly by changes in the amount of daylight entering the room, makes the control of the lighting levels on the working plane more complicated with a ceiling placed sensor. As mentioned above, the ceiling/workplane illuminance ratio is strongly depended on the position of the photosensor and its FOV [9, 11, 23]. The best correlation between these two illuminance values is achieved in areas away from exterior openings where light distribution is uniform. Nevertheless, these areas could not be considered as daylight zones where daylight can be exploited to its maximum extent [8, 24]. On the contrary, placing the sensor near the windows more energy savings are expected but with poorer performance in terms of achieving necessary lighting levels.
Consequently, all commissioning procedures should be considered during the design phase where critical decisions on component selection have to be taken. Since there is not any standard rule among manufacturers usually a trial and error method is used to obtain descent dimming response. The proposed sensor is designed with a variable FOV. This allows a modification in FOV in relation to the selected sensor placement. A narrow FOV is needed in order to track the changes of illuminance on the working plane accurately while a wider one can be used in order not to be influenced by the changes inside the room. Extending the FOV of the photosensor, the correlation between ceiling and workplane lighting levels is deteriorating and the perceived illuminance values by the sensor do not correspond proportionally to the illuminance levels on the working plane.
The operation principle to vary FOV with the telescopic cylinder is presented in Figure 1(a). During experimental procedure, three adjustments were made on the telescopic cylinder. Figure 1(b) illustrates the spatial response of the developed sensor for each of the three adjustments and Table 1 gives their corresponding acceptance angles. Numbers 1 to 3 correspond to adjustments of the telescopic cylinder from wide to narrow FOV. Number 0 corresponds to the photosensor without the telescopic cylinder.



(a) (b)

Figure 1. Variable FOV of sensor using a telescopic cylinder (a) and spatial responses for the selected adjustments of the telescopic cylinder (0 corresponds to a spatial response without the telescopic cylinder) (b).

Table 1. Acceptance angles for the selected adjustments of the FOV

Adjustment of the telescopic cylinder	Field of view (FOV)	Acceptance angle
0	Wide	180^o
1	Wide	97^o
2	Mid	69^o
3	Narrow	33^o

The spatial responses were measured with the use of a two-axis goniophotometer according to Bierman and Conway [16]. A clear 250W incandescent lamp (Osram, 64480KL) was used as a light source with filament size equal to 12mm. The distance between sensor and lamp was 140cm, making the incident light rays parallel (subtended angle: $0{,}491^o$). The correlation between sensor signal and illuminace value was performed with an integrating sphere [16], exposing the examined sensor and a calibrated one to known light levels. Different photocell signals were monitored by varying the incident light intensity. The spectrum of the light source (a 500W incandescent lamp Sylvania, SYL-180) was constant because the dimming was realized by using a mechanical variable aperture to limit the light flux entering the integrating sphere. Due to the uniform luminance field in the interior of the sphere, the sensor signal can be correlated with illuminance values. All measurements were performed in the Lighting Laboratory of the National Technical University of Athens. The experimental set up was in a dark room with dimensions of (20 m X 7 m X 4 m) with black mat painted surfaces [25]. Ambient temperature was maintained constant at 26^oC and input voltage at 230V AC, 50 Hz through the voltage stabiliser for all tested conditions.

3. Measurements

Figure 2 presents the developed sensor which was used during the experimental procedure. These were realized in a wooden scaled room (1:10) in which the sensor was mounted on the ceiling track aiming downwards while a photometer was placed on the working plane underneath the sensor. Figure 3 present the geometric configuration of the scaled room with the different sensor placement.

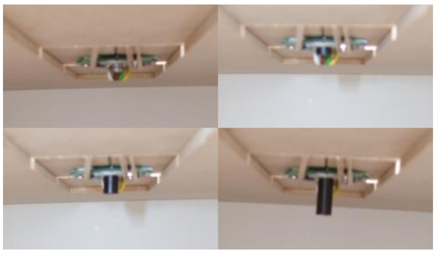


Figure 2. Sensor with variable FOV inside the scaled room.

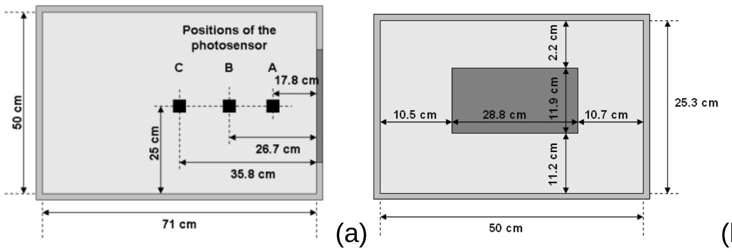


Figure 3. Floor plan of the scaled room with the various measurement positions (a) and south façade of the scaled room (b).

The scaled room was placed in an unobstructed open place on the roof of the Lighting Laboratory in the National Technical University of Athens that is located in Zografou, Athens, Greece with a south external façade. As presented in Figure 3 the sensor was placed in three different positions in the interior while three different FOVs (adjustments of the telescopic cylinder 1 to 3) have been used. The experiments took place between April and May 2007. Measurements were performed simultaneously and on an hourly basis from 8:00 to 18:00 LT for every selected position and FOV. The signal of the sensor and the illuminance values on the working plane were recorded constantly for all examined cases (Figure 4).

Figure 4. Experimental configuration.

Two types of glazing were used, clear and diffuse. Diffuse glazings have been used to create interior luminance distribution which can be simulated easily since no sky parts are visible. Measurements were taken during days with clear sky conditions. During the experimental procedure, radiation data from the University's meteorogical station were used. These data were also used to simulate the scene using Radiance [26]. Figure 5 illustrates the signal of the photosensor (as ceiling illuminance) in relation to the working plane illuminance in the room for the three positions and FOVs of the developed sensor. These data correspond to clear sky conditions (15/5/2007) while Figure 6 shows the same data using diffuse glazing (27/4/2007).

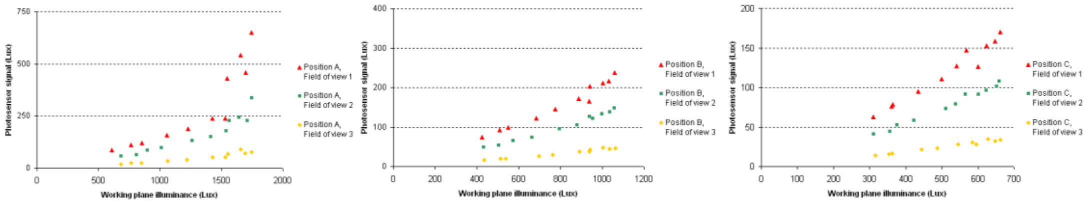


Figure 5. Ceiling illuminance (photosensor signal) at position A (left), B (middle) and C (right) with FOVs 1, 2 and 3 vs. working plane illuminance (clear sky, clear glazing, 15/05/2007).

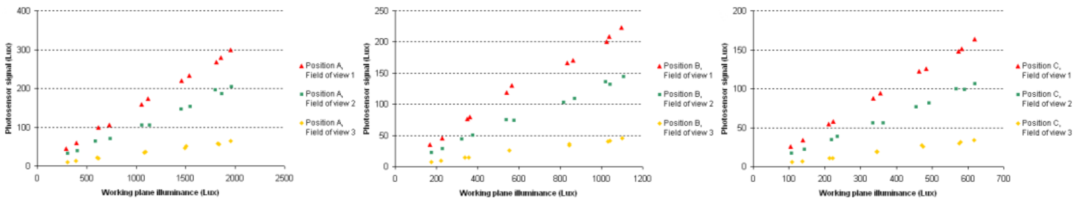


Figure 6. Ceiling illuminance (photosensor signal) at position A (left), B (middle) and C (right) with FOVs 1, 2 and 3 vs. working plane illuminance (clear sky, diffuse glazing, 27/04/2007).

Ideally for optimum control, the photosensor illuminance should be exactly proportional to the working plane illuminance. This is approximated when diffuse glazing is used but for clear glazing it is not always valid. There are occasions when the sensor underneath the ceiling sensor receives direct sunlight. In these cases the correlation gets worse and cannot be improved even by increasing the FOV of the ceiling sensor.

Thus the correlation of ceiling and working plane illuminance can be used as criterion for the sensor optimum placement and FOV. Linear regression with a high value of correlation coefficient is an indication that daylight harvesting control might regulate lighting levels properly. Since such ideal behaviour does not exist in the real world, the advantage of having a variable FOV will help designers to define proper placement by just examining correlation between ceiling and workpalne illuminance levels for various sensor FOVs and placements during the initial phase of the project. An example of this procedure is presented in Figure 7. Based on the total set of data during the experimental period, the optimum choice for the best performance of the developed sensor is position B with FOV adjusted to selection 2 (Table 2). At this point, it should be clarified that the correlation between ceiling and workplane illuminance levels is not the only criterion for the optimum control system performance. Achieved energy savings and adequacy of lighting levels should be taken into consideration. Although during the period of spring the commissioning procedure can be more representative, more days (embodying summer and winter periods) must be examined in order to achieve more accurate results.

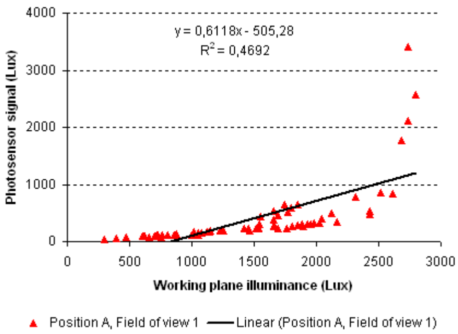


Figure 7. Ceiling illuminance (photosensor signal) at position A with FOV 1 vs. working plane illuminance (total number of days with clear and diffuse glazing April - May 2007).

Table 2. R^2 values for the simple linear correlation between sensor signal and workplane illuminance for all examined sensor FOVs and placements

Position on the ceiling	Field of view (FOV)	R^2 values
A	1	0,4692
A	2	0,4369
A	3	0,6625
B	1	0,9396
B	2	0,9622
B	3	0,9422
C	1	0,9292
C	2	0,9428
C	3	0,9413

For all the sets of ceiling/workplane illuminances with the same position but different FOV, t-test was applied in order for their homogeneity to be examined [27]. For all the cases the $|t|$ values were larger than the critical value t_α at the 5% confidence level in the two tailed tests (Table 3). Therefore the correlation values are affected statistically by both position and FOV. The non homogeneity of the R^2 values shows that different FOVs can affect overall performance.

Table 3. |t| values for testing the statistical significance of the correlation coefficient R^2, for all the samples (Position on the ceiling and FOV)

Position on the ceiling	Field of view	Field of view	|t| value	Homogeneity of the R^2 values
A	1	2	3,075	Non homogeneity
A	1	3	6,802	Non homogeneity
A	2	3	5,671	Non homogeneity
B	1	2	9,949	Non homogeneity
B	1	3	24,858	Non homogeneity
B	2	3	25,790	Non homogeneity
C	1	2	8,453	Non homogeneity
C	1	3	22,629	Non homogeneity
C	2	3	21,212	Non homogeneity
Critical value t_α=1,997 at a confidence level of 0,05 (α=0,05) in the two tailed tests.				

4. Simulations

Since measurements cannot be performed during the design phase of a daylight control system, a simulation approach is needed to supply all necessary data to fine tune the system. In order to assure that the performance of the developed sensor can be simulated accurately, a comparison analysis was made between measured and simulated illuminance values.

The input data for the simulation analysis were a) room geometry and optical properties of its interior surfaces, b) sensor cover geometry (Figure 8) and c) hourly meteorological data of the corresponding days (15/05/2007 using clear and 27/04/2007 diffuse glazing). Optical properties were measured in the Lighting Laboratory [25] according to related standards [29] and are presented in Table 4. Radiation data were collected from the University Meteo station which was located nearby. Radiance [26] was used to simulate illuminance interior values. Clear sky conditions have been generated using Radiance third party “Gendaylit” algorithm based on the Perez model [28] which can create sky luminance distribution from direct and diffuse radiation data.

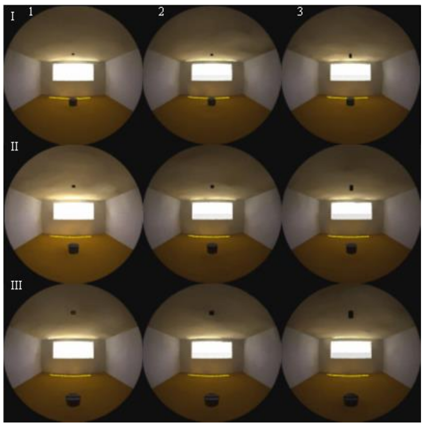


Figure 8. Radiance hemispherical images from scaled model interior. The three rows correspond to the respective sensor positions (A, B, C) and the three columns to the respective sensor cover geometries (FOV 1 to 3).

Table 4. Optical properties of interior surfaces of the scaled room

Interior surfaces	Color	Reflectance	Transmittance
Ceiling	Light brown	0,45	-
Walls	White	0,65	-
Floor	Brown	0,20	-
Window	Clear	-	0,64
Window	Milky	-	0,20

Figure 9(a) illustrates an example of the distribution of measured and simulated ceiling and working plane illuminance values from 8:00 to 18:00 LT when clear glazing was used (15/05/2007), for position A and FOV 1. Figure 9(b) illustrates similar example but using diffuse glazing (27/04/2007). Applying the paired t-test to compare measured and simulated data, it was found that these are statistically equal for all cases at a confidence level of α=0,01 (Table 5). The greater t values on 27/04/2007 mean that correlation was better when diffuse glazing was used resulting in a better control performance under overcast sky conditions.

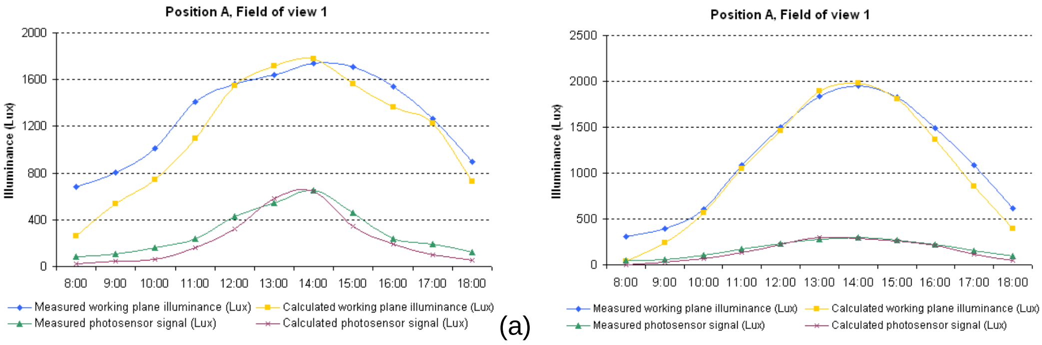


Figure 9. Distribution of measured and calculated illuminance values within 8:00 to 18:00 LT, between working plane and ceiling for position A and FOV 1 (15/05/2007) (a) and with diffuse glazing (27/04/2007) (b).

Table 5. t values for best fitting of the calculated values to the measured one

Position on the ceiling	Field of view (FOV)	t values			
		Clear sky Clear glazing (15/05/2007)		Clear sky, Diffuse glazing (27/04/2007)	
		Working plane	Photosensor signal	Working plane	Photosensor signal
A	1	0,0101	0,0170	0,0293	0,0201
A	2	0,0164	0,3958	0,0442	0,0109
A	3	0,0105	0,0146	0,0741	0,0282
B	1	0,0192	0,0102	0,1397	0,0113
B	2	0,0141	0,0308	0,1241	0,0162
B	3	0,0172	0,0329	0,1119	0,6892
C	1	0,0111	0,1057	0,8249	0,6716
C	2	0,0140	0,0127	0,9100	0,0566
C	3	0,0129	0,0178	0,8370	0,8993

The critical value t_{α} is the confidence level of 0,01

5. Conclusions

While new technologies show some promise, it is not clear if these can be widely incorporated in the building sector. Conventional photosensors have not yet been obsolescent since they can perform better and be less expensive than CCD or CMOS image sensors. Thus, substantial effort is needed to further improve their performance.

This paper introduces a new type of sensor with variable FOV using a telescopic cylinder. This is the main improvement over existing sensors with a really simple operation during commissioning. Using simulation data, during the design phase, a proper definition of sensor position and FOV can be established improving the overall performance of the control system (closed loop, constant set-point). As a result, the sensor can satisfy one performance criterion which is the linear correlation between sensor and workplane illuminance levels.

Since FOV can affect the lighting adequacy of workplane lighting levels and energy savings, future work must be focused on embodying the above parameters as two additional criteria for the optimum placement of the photosensor. The aim of this study wasn't just to point the optimum position or FOV of the developed photosensor but to demonstrate a new general approach.

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