CamSensor: A Novel Lighting Control System Integrating High Dynamic Range Imaging and DALI

Abhijit Sarkar, MS and Richard G. Mistrick, Ph.D., P. E., FIES

Abstract – Conventional photosensor based lighting control systems rely on an integrated photosensor signal that senses the overall illuminance level within a space. All surfaces within the field of view of the photosensor as well as their reflectance values influence this signal.

This paper presents a new method for lighting control using an inexpensive image sensor as the light sensing device in conjunction with a computer graphics technique called High Dynamic Range imaging. A wide range of lighting levels can be determined using this technique. A single sensor is capable of estimating the illuminance levels simultaneously at multiple locations on the workplane. This paper describes a calibration procedure to derive space illuminance information from the images during system operation. It also provides an algorithm to control each luminaire individually so as to achieve different target illuminances at different points on the workplane. The solution takes full advantage of the powerful features of digital technologies, including digital imaging and Digital Addressable Lighting Interface (DALI) ballasts. This novel solution, described as CamSensor in this paper, is a proof-of-concept for the application of High Dynamic Range imaging in the field of lighting control.

Keywords – Digital Addressable Lighting Interface (DALI), High Dynamic Range imaging, daylighting, photosensors, lighting control

1 BACKGROUND

1.1 PHOTOSENSOR-BASED LIGHTING CONTROL AND ITS LIMITATIONS

Photosensor-based lighting control is a common method for daylight harvesting in buildings. However, the use of photosensors to control interior lighting is nontrivial. Since the photosensor signal greatly depends on the position of the sensor relative to room surfaces and daylight apertures, and on room surface material properties, commissioning and calibration play a pivotal role in photosensor applications. Various problems associated with calibration and commissioning contribute to the fact that photosensor-based systems have seen limited application and have traditionally faced a market barrier. (Rubinstein and others 1999; Kim and Mistrick 2001; Mistrick and Thongtipaya 1997; Mistrick and Sarkar 2005)

1.2 DIGITAL ADDRESSABLE LIGHTING INTERFACE

A new technology called Digital Addressable Lighting Interface (DALI) is now available for automatic lighting control, which enables dimming of individual luminaires to different levels. DALI is an industry standard open protocol for digital communication between the individual components of a lighting system. DALI incorporates simplified communication methods providing optimum functionality, and therefore is simpler and more cost-effective than many other complex Building Management Systems. It also allows exchangeability of dimming ballasts from different manufacturers. (DALI–AG 2001)

Dimming of individual ballasts allows a DALI-based lighting control system to achieve different electric light output levels in different areas across a space providing for more precise control of the lighted environment. It would be very difficult to implement this kind of control in a daylighted space with current photosensor technology. Hence there is a need for an advanced daylight sensor that can reap the benefits and flexibility that a lighting control technology like DALI offers.

1.3 AN IMAGE SENSOR AS A LIGHT-SENSING DEVICE

This paper proposes the use of an inexpensive CMOS image sensor as a light-sensing device, as an alternative to a photosensor. Additionally, a technique called High Dynamic Range (HDR) imaging, much used in computer graphics, is employed. Many of the problems associated with integrating photosensors can be circumvented using the hardware and software associated with this solution. The solution, described as CamSensor in this paper, is a proof-of-concept for the application of HDR imaging in the field of lighting control.

The only published research work (Glennie and others 1992) on the application of solid state imaging in lighting control involved a prototype consisting of a calibrated CCD camera with a resolution of 165 X 192 pixels, an image acquisition board, a personal computer and peripheral lighting control gear. The concept was to compute the surface luminance at various locations in the room and use that information to adjust luminaire output to maintain desired lighting levels. The paper also proposed to detect events that required a specific luminance profile and adjust the electric lights accordingly. The operation of the system involved segmentation of the image in order to detect key surfaces, specifying desired luminance values and identifying the key tasks in the space by means of simple heuristics. However, the capabilities of this prototype were rather limited and full performance analysis was not provided. Further research work on this application was never reported.

1.4 HIGH DYNAMIC RANGE IMAGING

The relationship between the pixel values obtained from digital (or analog) images and the light striking the image sensor during image capture is generally nonlinear because of several nonlinear mappings. This is true for CCD (which has a linear response) as well as CMOS (which typically has a nonlinear response) sensor-based imaging devices. This nonlinear relationship is unique for a given imaging device and is known as the camera response function. The camera response function can be derived mathematically by considering multiple pictures of the same scene with different exposures (Debevec and others 1997; Sarkar 2005). This technique is called High Dynamic Range (HDR) imaging. The dynamic range is the range of subject brightness values over which a change in subject brightness will create a change in image brightness. The HDR technique helps extend the limited dynamic range of the imaging device by combining exposure-bracketed images. This is necessary to account for under or overexposed areas within a single image. Using this method, luminance can be determined across a wide range of values. HDR can work even with direct sunlight present in an image.

2 DESCRIPTION OF THE COMPONENTS OF CAMSENSOR

CamSensor consists of both hardware and software components as described below:

- **Camera Module:** The prototype, shown in fig. 1, consists of a 1/3” color camera module using a CMOS image sensor OV7620 manufactured by Omnivision. All camera functions, such as exposure (digital value varying from 0 to 255), gamma, gain, white balance, color matrix, windowing etc are programmable. (Omnivision 2001)

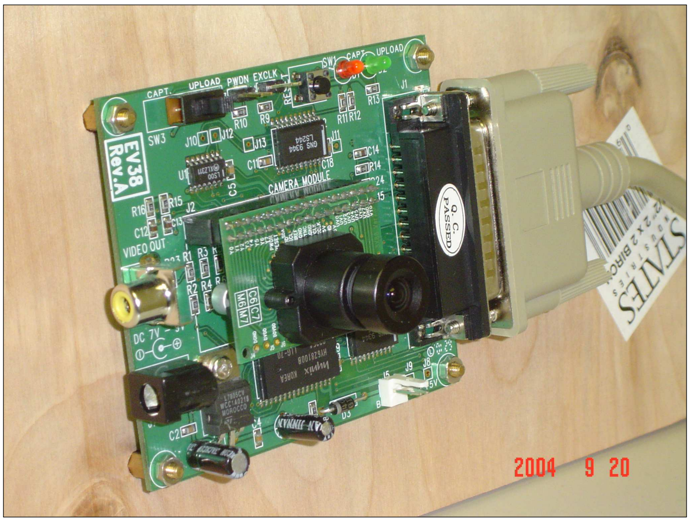


Fig. 1. CEV38 evaluation board with C3188A

- **Master Control:** The computer that oversees the entire system
- **CamSensor software:** The software for CamSensor includes an HDR imaging algorithm (for determining luminance from the images) and a lighting control algorithm (for determining and setting the appropriate dimming levels of the DALI luminaries using DALI communication protocol). The former has been developed in Matlab and the latter in C.
- **DALI Controller:** This is the bridge between the computer and the luminaires and converts an RS232 signal to DALI communication protocol. A Tridonic Busmaster was used for this setup.

3 CAPABILITIES OF CAMSENSOR

Following is a list of the advantages that can be expected from a full-fledged product arising out of CamSensor. However, only the first two aspects were investigated in this research.

1. A single sensor can monitor different task areas with different target illuminance values, provided these task areas are within view of the camera.
2. A lower resolution, less expensive CMOS sensor can be used for image capturing.
3. Direct view of luminaires or windows is permissible, as long as blooming (the effect when an oversaturated pixel affects the surrounding pixels) is minimal.
4. The system can be designed to account for reflectance changes to the key target surfaces by sensing surface color and automatically shifting to neighboring pixels when needed.
5. CamSensor can be operated as an embedded system, with all processing carried out locally, or an Ethernet for remote processing to achieve greater flexibility.

6. CamSensor may be used to sense occupancy through detection of movement within the image.

However, CamSensor is not a universal solution and may not be appropriate under certain conditions. Limitations of this system will be discussed at the conclusion of this paper.

4 RELATIONSHIP BETWEEN THE ARC POWER LEVEL OF A DALI LUMINAIRE AND THE MEASURED ILLUMINANCE AT DIFFERENT TEST POINTS

Since CamSensor uses DALI technology, it is important to determine the relationship between the arc power levels of the DALI ballasts and the corresponding light output from the DALI luminaires. For example, if a luminaire arc power input is changed from 100% to 50%, does the illuminance at a test point change by 50% as well?

Tests were performed on two T8 (2L-32W) luminaires (L-1 and L-2) and four T5 (2L-54W) luminaires (L-3 through L-6). Each luminaire was individually dimmed from 100% to 10% in steps of 10% and the illuminance level was recorded at a point on the workplane directly below the luminaires.

Figure 2 plots the percent of maximum illuminance for the different luminaires at different percent dimming levels. As is evident from the graph, the relationship between lamp output and the dimming level (or arc power level) of the DALI luminaire follows a slightly nonlinear pattern. This is likely due to the fact that DALI ballasts follow a logarithmic dimming curve.

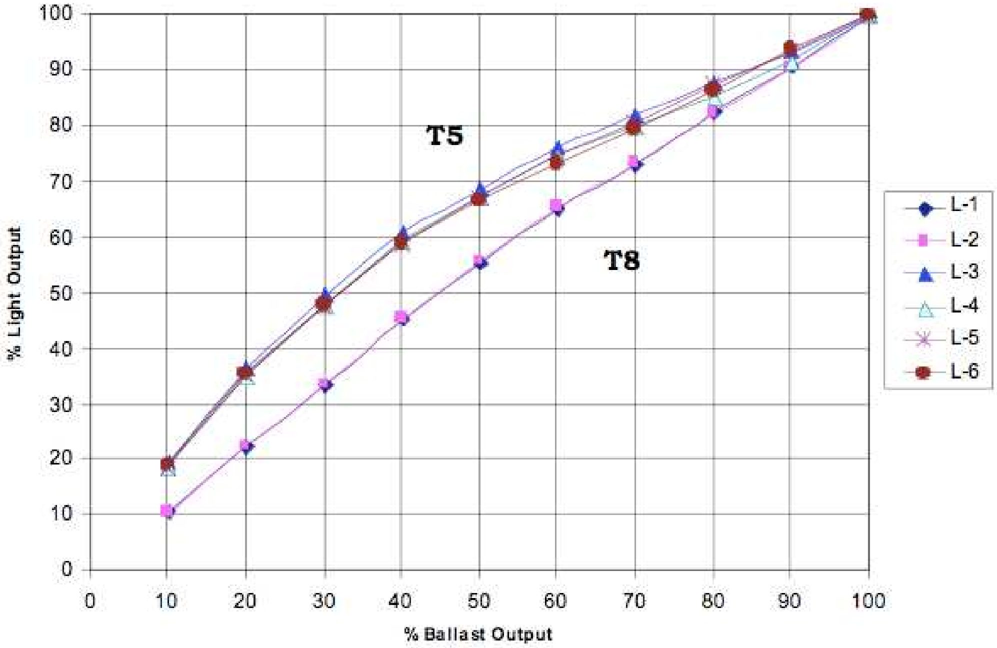


Fig. 2. Relationship between the percent illuminance level and percent ballast output at

different test points

5 APPLYING CAMSENSOR TO DAYLIGHT CONTROL WITH DALI

5.1 TEST SETUP

A large classroom space was used to test the CamSensor system. Six recessed DALI luminaires were used as dimmable electric lights to be controlled by the CamSensor software. L-1 and L-2 were direct VDT fixtures (2 lamps, T8, 32W), while L-3, L-4, L-5 and L-6 were recessed louvered direct fixtures (2 lamps, T5, 54W). All luminaires were fitted with fluorescent lamps with similar Correlated Color Temperature (CCT) and thus, similar Spectral Power Distribution (SPD).

A total of 12 target points (also referred to as test points) were selected, where specified target illuminance levels were to be maintained.

Figure 3 shows the test room, with the layout of the six luminaires and twelve test points.

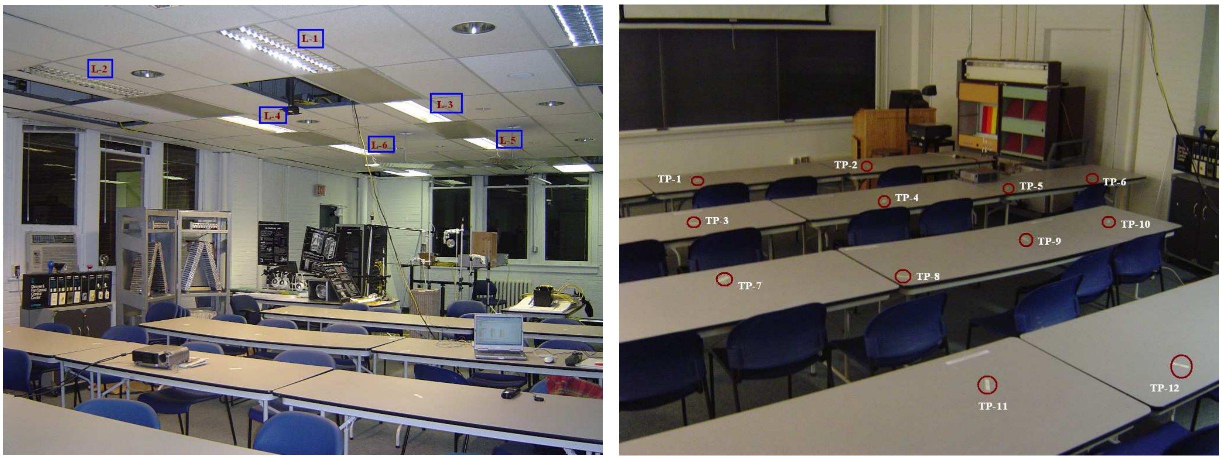


Fig. 3. Six DALI luminaires and twelve test points

The camera was mounted approximately 1.52 meters (5 feet) above the desks. It was placed in a position that provided a view of all twelve test points. Figure 4 shows the location of the camera.

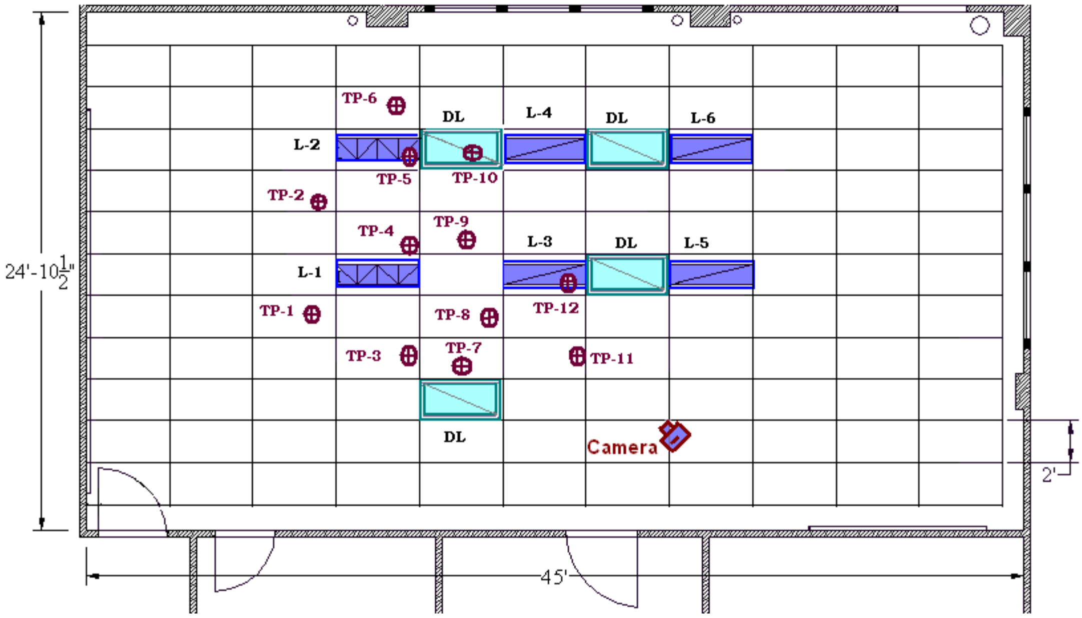


Fig. 4. Ceiling plan of the lighting laboratory showing the locations of the luminaires and test points

5.2 NOTATIONS USED IN THIS SECTION

CF_{expX} : Calibration factor for converting image radiance values at exposure X, to corresponding luminance values.
E_{ref} : Illuminance on the reference Lambertian surface.
$R_{ref\text{-}expX}$: Image radiance of the reference Lambertian surface at exposure X.
ρ_{ref} : Reflectance of the reference Lambertian surface.
$L_{ref\text{-}LX\text{-}Y}$: Luminance at test point Y due to luminaire X on the reference Lambertian surface.
$E_{LX\text{-}Y}$: Estimated illuminance at test point Y due to luminaire X.
$L_{ref\text{-}DL\text{-}Y}$: Luminance at test point Y due to daylight with reference Lambertian surfaces.
$E_{DL\text{-}Y}$: Estimated illuminance at test point Y due to daylight.
$L_{LX\text{-}Y}$: Luminance at test point Y (desk surface) due to luminaire X.
L_Y : Luminance at test point Y due to daylight and electric light.
$L_{DL\text{-}Y}$: Luminance at test point Y due to daylight only.
$E_{TARG\text{-}Y}$: Target illuminance level at test point Y
x_{LX} : Required fractional light output for luminaire X that best achieves the desired illuminance levels at different test points on the work plane
d_{LX}: Present light output of DALI luminaire X, as a fraction of maximum output.

We now formulate the steps needed to ensure proper calibration and operation of CamSensor. For the present prototype, the image capturing process is manual and components of the software are run separately. However in a full-fledged system, this entire process would be automatic.

5.3 CALIBRATION

Since CamSensor does not directly measure illuminance, calibration is necessary to obtain illuminance from image pixel values. There are two steps in the calibration procedure, 1) conversion of pixel radiance to luminance and 2) conversion of luminance to illuminance. The first conversion factor depends on the exposure setting of the image and can be determined through a one-time calibration, described hereafter as factory calibration. The second factor can be determined by a calibration procedure, described hereafter as site calibration, which must be performed for the space being controlled.

An important requirement for an accurate calibration is to use a Lambertian (or close to Lambertian) surface with known reflectance. In a separate experiment (Sarkar 2005) it was determined that among all available options, bleached flour pressed evenly onto a piece of paper of size 15.2 cm x 20.3 cm (6" x 8") worked the best. Reflectance of the bleached flour was determined to be 74.7%. For a full-fledged system, pressed Barium Sulphate or Polytetrafluoroethylene (PTFE) can be good candidate as a Lambertian surface.

5.3.1 FACTORY CALIBRATION

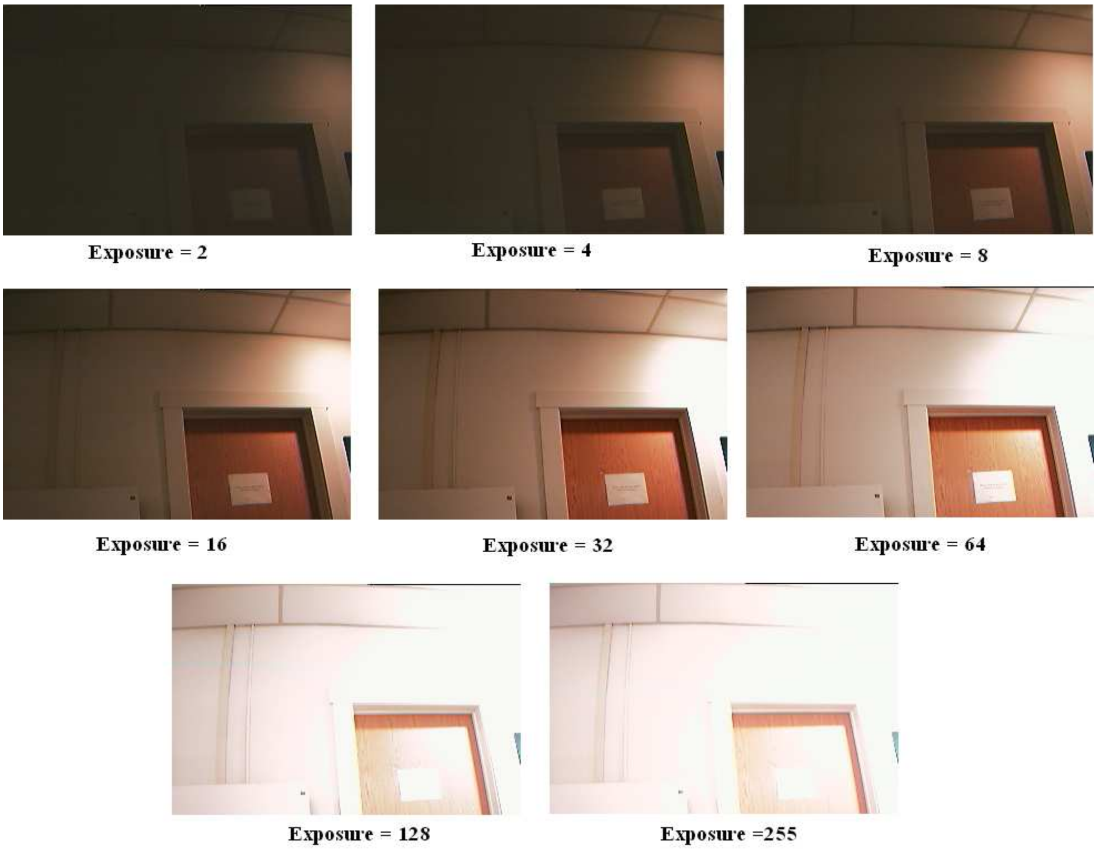
To conduct the factory calibration, eight images of a high contrast scene (where part of the scene is very bright and another part is relatively dark) are captured with different exposure settings (Fig. 5). The exposure settings used in this step were: 2, 4, 8, 16, 32, 64, 128 and 255. The images are then input to the High Dynamic Range imaging algorithm and the following steps are completed.

1. Approximately 50 pixels are automatically selected from the image with exposure = 32. These pixels must be evenly distributed throughout the image and have a limited variation of their values from adjacent pixels. Here, the value at a pixel refers to its relative radiance (or luminance, in photometric terms) given by the Y value in the CIE XYZ chromaticity coordinates, as determined from the RGB values. An average value of the eight pixels surrounding the test pixel plus the test pixel itself is used for computing the radiance value at a test point. (Sarkar 2005)
2. The High Dynamic Range imaging algorithm is then used to determine the image response function based on the average radiance of the chosen pixels at each exposure setting. This response function is a table of 256 values that can be used to compute the absolute luminance value at a pixel from the CIE Y value. The response function is stored in the master control computer for future reference.
3. Next, the calibration factors that convert the relative radiance values to corresponding absolute luminance are determined. Note that for a given exposure setting, the radiance values obtained from an image are proportional to the corresponding luminance values. The calibration factors are nothing but proportionality factors, which depend on the camera settings like exposure, aperture time etc. All camera settings other than the exposure are constant for CamSensor. Thus, there is a calibration factor for each exposure setting. To determine these calibration factors, images of a scene are captured with all exposure settings to be used during system operation, typically, 4, 8, 16, 32, 64

and 128. A Lambertian surface with known reflectance is placed within the scene and its illuminance is measured. The average relative radiance ($R_{\text{ref-expX}}$) on this surface is then determined for each exposure setting using the response function. The calibration factor (CF) at a particular exposure can be computed from (1), which is the same at each pixel for a given image. Using this calibration factor, the luminance can be obtained from the radiance value at any test point Y from an image captured with exposure setting X, as shown in (2).

$$CF_{\text{expX}} = E_{ref} / (R_{\text{ref-expX}} * \pi / \rho_{\text{ref}}) \tag{1}$$

$$L_Y = R_Y * CF_{\exp X} \tag{2}$$



Exposure = 2

Exposure = 4

Exposure = 8

Exposure = 16

Exposure = 32

Exposure = 64

Exposure = 128

Exposure =255

Fig. 5. Images captured to determine the image response function

5.3.2 SITE CALIBRATION

In this part of the calibration, the objective is to determine the illuminance contribution due to different luminaires at the workplane target points. No electric light other than the DALI luminaires should be present at this stage.

In the discussion that follows, all images are captured with an *optimum exposure* setting, unless otherwise mentioned. Here, *optimum exposure* refers to an exposure that allows sufficient integration time, yet does not cause saturation near the target points in the image. If any of the test points is saturated (with a pixel value of 255), the exposure must be reduced. The correct exposure can be determined by trial and error.

1. First, capture an image of the scene and identify the target points. These specified image coordinates will be used during the calibration and operation of CamSensor. If the camera position changes for any reason, calibration must be redone.
2. Capture images of the workplane with the luminaires at full output, one luminaire at a time, and with reference Lambertian surfaces placed on the target points. Lamp output must be stable when this image is taken. No daylight should be present. From these images, the luminance values at the different points ($L_{ref\text{-}LX\text{-}Y}$) with the Lambertian reference surface are obtained for each luminaire. The corresponding illuminance ($E_{LX\text{-}Y}$), is obtained from (3).

$$E_{LX\text{-}Y} = L_{ref\text{-}LX\text{-}Y} * \pi / \rho_{ref} \tag{3}$$

3. Capture an image of the workplane for a typical daylight condition, with Lambertian surfaces placed at the target points. No electric light source should be present. (4) computes the illuminance at any test point Y due to daylight.

$$E_{DL\text{-}Y} = L_{ref\text{-}DL\text{-}Y} * \pi / \rho_{ref} \tag{4}$$

4. Capture an image of the workplane for the daylight condition used in the previous step, with the Lambertian surfaces removed. Compute the luminance $L_{DL\text{-}Y}$ at each point from this image. One or more extra test points with a Lambertian surface can be used to verify that daylight has not changed between steps 3 and 4.
5. Capture images of the workplane with each luminaire at full output, one at a time, with the Lambertian surfaces removed**.** From these images, the luminance at each target point ($L_{LX\text{-}Y}$) due to each luminaire can be obtained.
6. Determine the ratio $L_{ref\text{-}DL\text{-}Y}$ / $L_{DL\text{-}Y}$ at the different points for a typical daylight condition and stored for future use.
7. Specify the target illuminance ($E_{TARG\text{-}Y}$) in terms of % of full electric light at the different points.

If there is any change in the configuration of the room causing a change in a test point location or the surface material at a location, site calibration must be performed again for that point.

The fact that daylight conditions (in intensity and direction) are constantly changing has a potential to affect CamSensor performance. The above calibration method considers a typical daylight condition to compute the luminance ratio L_{ref}/L_{DESK} in order to estimate the illuminance contribution due to daylight during system operation. This ratio is likely to be more stable if the camera is looking away from the daylight source.

5.4 OPERATION

1. Capture an image of the task area with an *optimum exposure* as previously described. If no exposure meets this requirement, a High Dynamic Range imaging technique must be applied (this could potentially occur when high levels of daylight are present at one or more target points).
2. Determine the present dimming levels of individual luminaires (d_X) by querying the ballasts in the controlled luminaires.
3. Determine the luminance due to daylight at each target point by subtracting out the expected electric light contribution, then compute the estimated daylight illuminance at each point as follows:

$$L_{DL\text{-}Y} = L_Y - (d_{L1} * L_{L1\text{-}Y} + d_{L2} * L_{L2\text{-}Y} + ... + d_{L6} * L_{L6\text{-}Y}) \tag{5}$$

$$E_{DL\text{-}Y} = L_{DL\text{-}Y} * (L_{ref\text{-}DL\text{-}Y} / L_{DL\text{-}Y}) * \pi / \rho_{ref} \tag{6}$$

4. Using (7), the new required dimming level for each of the individual DALI luminaires is determined by solving for $x_{L1}, x_{L2}, ..., x_{L6}$ using the least square method.

$$\left.\begin{array}{r} x_{L1} * E_{L1\text{-}1} + x_{L2} * E_{L2\text{-}1} + ... + x_{L6} * E_{L6\text{-}1} = E_{TARG\text{-}1} - E_{DL\text{-}1} \\ x_{L1} * E_{L1\text{-}2} + x_{L2} * E_{L2\text{-}2} + ... + x_{L6} * E_{L6\text{-}2} = E_{TARG\text{-}2} - E_{DL\text{-}2} \\ ... \\ x_{L1} * E_{L1\text{-}12} + x_{L2} * E_{L2\text{-}12} + ... + x_{L6} * E_{L6\text{-}12} = E_{TARG\text{-}12} - E_{DL\text{-}12} \end{array}\right\} \tag{7}$$

   In matrix form,

$$[E] \bullet [x] = [E_{TARG} \text{-} D]$$

   Where,
   [E] is the matrix for different luminaire contributions at different test points
   [x] is the matrix for the light output levels of the different luminaires
   [E_{TARG} -D] is the matrix for the required electric light contributions at different test points (D signifies daylight contribution).

5. The dimming level of each DALI luminaire is then updated by sending appropriate DALI commands to change the luminaire output to the levels determined in the previous step.
6. After a certain interval of time (set by the user of CamSensor), repeat steps 1 through 5.

5.5 A TEST OF THE SYSTEM

This experiment follows the calibration and operational steps described in the previous section. A series of experiments showed that conversion of radiance to luminance involved more error when the luminance level was low. This is related to the signal-to-noise (S/N) ratio of the image sensor. In order to improve the S/N ratio and estimate the luminance at a given test point more accurately, additional luminaires were turned on to maintain a higher light level during the image capturing process. This additional contribution was subtracted out during the computations. In a full-fledged system capable of detecting low luminance variation, this adjustment would not be necessary.

Daylight penetration in the lighting laboratory where the research was carried out was insufficient, so four 2' X 4' lensed troffers were chosen to simulate diffuse daylight. The simulated daylight level was not varied, but the operational procedure to address variations would be the same.

The following luminaires were used in this experiment (see Fig.4):

Dimmable DALI luminaires (L1 through L6) – Two T8 (2L-32W) luminaires (L-1 and L-2) and four T5 (2L-54W) luminaires

Luminaires for simulating daylight (DL) – four recessed 2 X 4 troffers (4 lamps T8 32W)

Luminaires for background light (ND) – four CFL downlights (CFL 42W) each dimmed to 30%.

As stated before, bleached flour pressed evenly on a diffuse white bond paper was used as the reference Lambertian surface in this experiment. The size of these surfaces was 11"x17" for test point 1 and 2 and 8.5"x11" for the test points 3 through 12. A larger area was necessary for the remote test points because of the low resolution of the camera.

5.5.1 FACTORY CALIBRATION

Table 1 shows the factory calibration factors for the different exposure settings. These values were obtained by comparing luminance meter readings and computed radiance values at an arbitrarily chosen test point.

TABLE 1. Calibration factors based on exposure setting

Exposure	CF (exposure)
4	8.103
8	8.229
16	8.638
32	9.394
64	10.436
128	11.004

5.5.2 SITE CALIBRATION

Luminance was computed at each test point from the images acquired for each luminaire's contribution. Figure 6 plots computed luminance values from the CamSensor system versus measured luminance values taken from the direction of the camera for different test points and different light sources.

Using the calibration procedure described above (using bleached flour as the reference Lambertian surface) to relate target point luminance to illuminance, illuminance values were then estimated from the computed luminance levels at the different points. Figure 7 plots CamSensor reported illuminance values against measured illuminance values for the different test points and light sources.

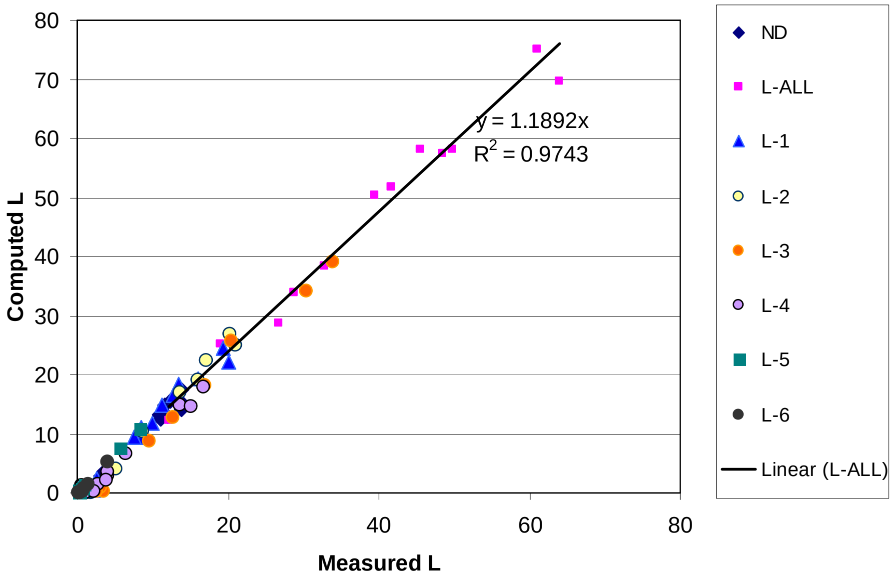


Fig. 6. Measured vs. CamSensor reported luminance values (in cd/m^2) at different test points due to each light source

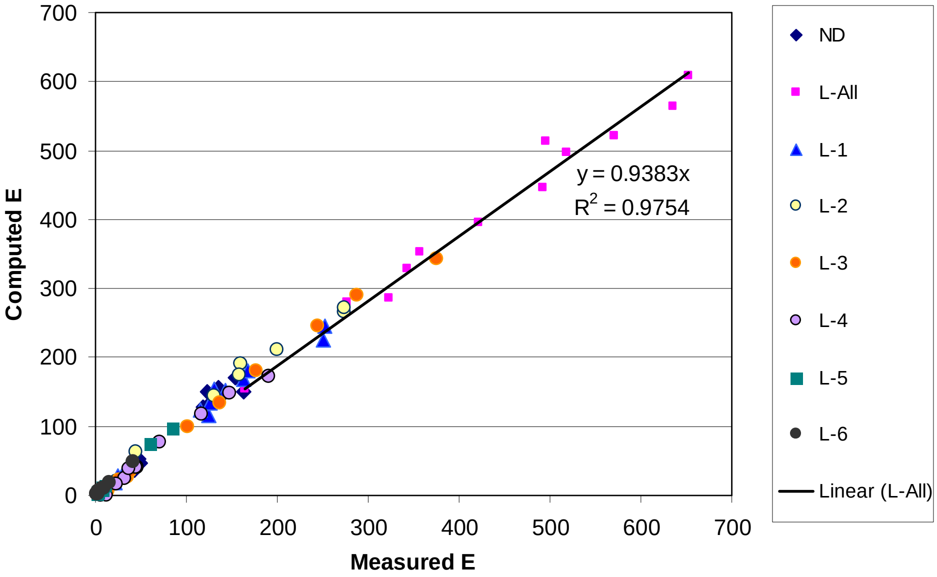


Fig. 7. Measured vs. CamSensor reported illuminance values (in lux) at different test points due to each light source

The ratio of luminance with and without the Lambertian surface for the typical daylighting condition is given in Table 2. These values were used to estimate daylight level during operation. It is important to note the variations in these values due to the non-Lambertian nature of the desktop. This is the reason why Lambertian surface calibration is necessary.

TABLE 2. Ratio of (L_{ref} / L_{DESK}) for typical daylight

Luminaire	**TP1**	**TP2**	**TP3**	**TP4**	**TP5**	**TP6**
Typical DL	3.57	3.192	2.451	2.546	2.33	2.645

Luminaire	**TP7**	**TP8**	**TP9**	**TP10**	**TP11**	**TP12**
Typical DL	2.163	2.237	2.225	2.203	2.167	1.671

The target illuminance level was set at 90% of the total contribution due to the dimmable DALI luminaires (L1 – L6) at each target point. Table 3 shows the target illuminance levels at the different test points.

TABLE 3. Target illuminance levels (lux) at different test points

TP1	**TP2**	**TP3**	**TP4**	**TP5**	**TP6**
125.4	255	247.3	476.5	442.8	320.4

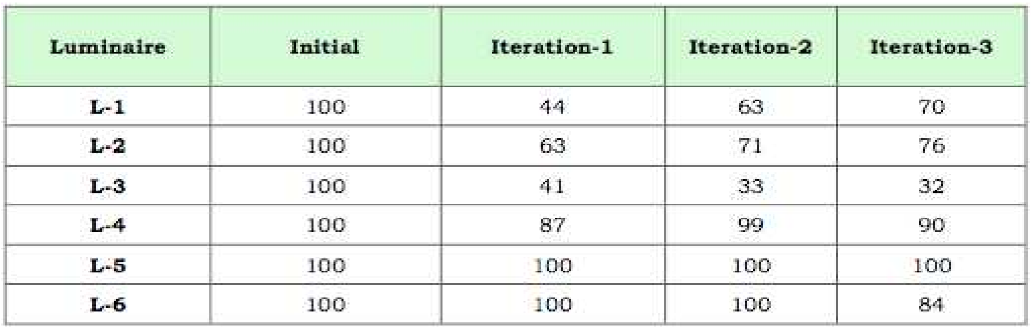
TP7	**TP8**	**TP9**	**TP10**	**TP11**	**TP12**
308.3	509.2	651	528.4	412.3	571

5.5.3 OPERATION AND RESULTS

Table 4 shows the percent illuminance levels determined by the dimming algorithm during three successive control algorithm iterations. Note that if the current illuminance was accurately estimated at all test points, the required illuminance levels (and the corresponding DALI dimming levels) could be precisely computed at the very first iteration. But, the error in illuminance predicted by CamSensor led to an adjustment in the luminaire light levels across successive iterations. This estimation error is considerably more for test points 1 and 2 as they are farthest from the camera. Because of the smaller projected areas seen by the camera, less number of pixels is available around these test points for estimating the luminance, thus causing more error in luminance estimation at test points 1 and 2. It results in more fluctuation in the dimming levels of L-1 (luminaire closest to these test points) determined by the algorithm. This problem can be solved by choosing test points closer to the camera or by using a camera with higher resolution.

In another area of interest, if a luminaire contributes little to any target point, a change in its dimming level will not result in much change in the illuminance at the test points. This may cause the luminaire to be overly sensitive to small deviations in predicted illuminance, unless additional constraints are introduced in the algorithm.

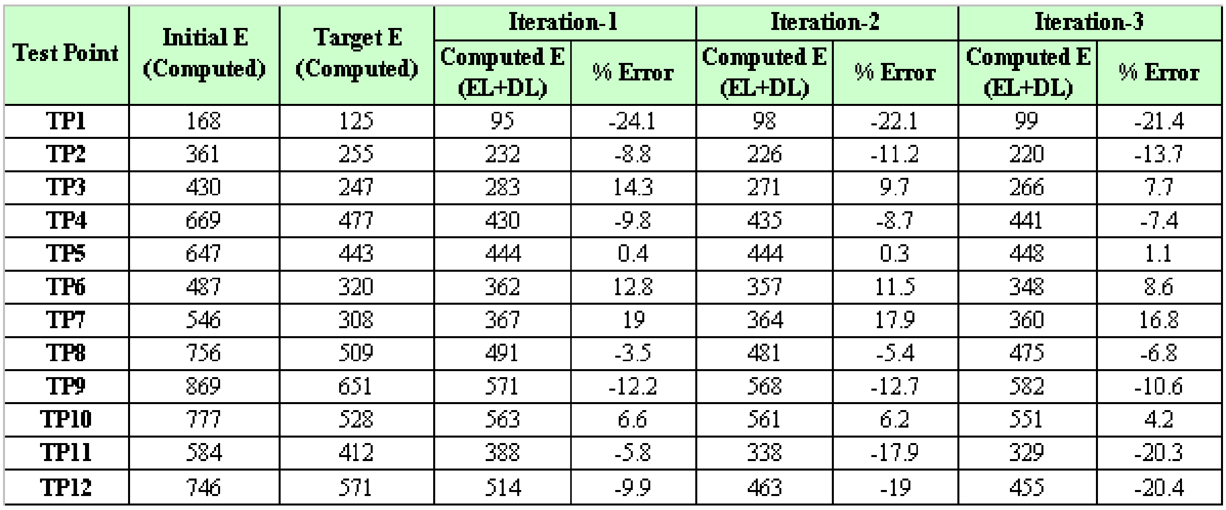
TABLE 4. Percent illuminance levels determined by the dimming algorithm during the three iterations



Luminaire	Initial	Iteration-1	Iteration-2	Iteration-3
L-1	100	44	63	70
L-2	100	63	71	76
L-3	100	41	33	32
L-4	100	87	99	90
L-5	100	100	100	100
L-6	100	100	100	84

Table 5 compares the CamSensor computed values of target and predicted illuminance due to daylight and electric light after each of the three iterations. Estimated errors in reaching the target illuminance levels are also shown.

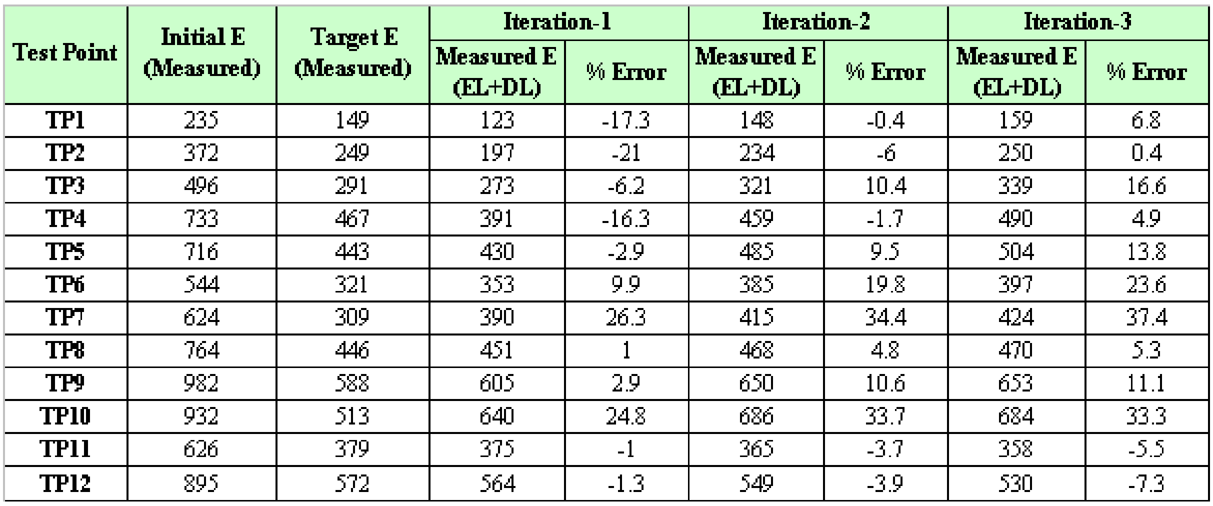
TABLE 5. Target and predicted illuminance (lux) due to daylight and electric light (lx) as computed after each iteration



Test Point	Initial E (Computed)	Target E (Computed)	Iteration-1		Iteration-2		Iteration-3	
			Computed E (EL+DL)	% Error	Computed E (EL+DL)	% Error	Computed E (EL+DL)	% Error
TP1	168	125	95	-24.1	98	-22.1	99	-21.4
TP2	361	255	232	-8.8	226	-11.2	220	-13.7
TP3	430	247	283	14.3	271	9.7	266	7.7
TP4	669	477	430	-9.8	435	-8.7	441	-7.4
TP5	647	443	444	0.4	444	0.3	448	1.1
TP6	487	320	362	12.8	357	11.5	348	8.6
TP7	546	308	367	19	364	17.9	360	16.8
TP8	756	509	491	-3.5	481	-5.4	475	-6.8
TP9	869	651	571	-12.2	568	-12.7	582	-10.6
TP10	777	528	563	6.6	561	6.2	551	4.2
TP11	584	412	388	-5.8	338	-17.9	329	-20.3
TP12	746	571	514	-9.9	463	-19	455	-20.4

Table 6 compares the measured values of target and achieved illuminance due to daylight and electric light after each of the three iterations.

TABLE 6. Target and achieved illuminance (lux) due to daylight and electric light (lx) as measured after each iteration

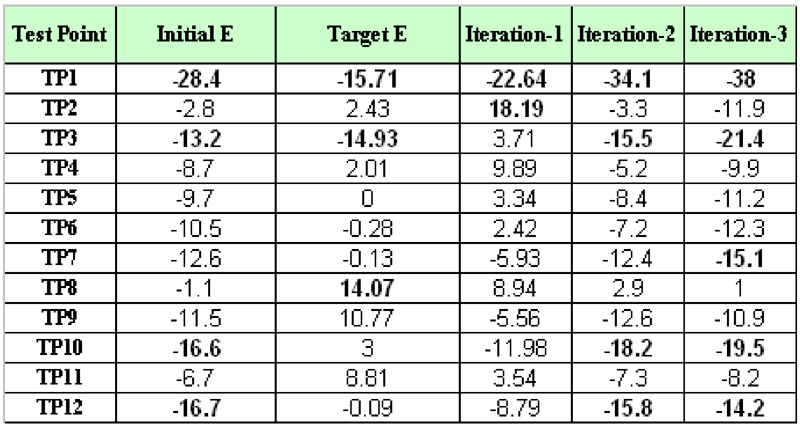


Test Point	Initial E (Measured)	Target E (Measured)	Iteration-1		Iteration-2		Iteration-3	
			Measured E (EL+DL)	% Error	Measured E (EL+DL)	% Error	Measured E (EL+DL)	% Error
TP1	235	149	123	-17.3	148	-0.4	159	6.8
TP2	372	249	197	-21	234	-6	250	0.4
TP3	496	291	273	-6.2	321	10.4	339	16.6
TP4	733	467	391	-16.3	459	-1.7	490	4.9
TP5	716	443	430	-2.9	485	9.5	504	13.8
TP6	544	321	353	9.9	385	19.8	397	23.6
TP7	624	309	390	26.3	415	34.4	424	37.4
TP8	764	446	451	1	468	4.8	470	5.3
TP9	982	588	605	2.9	650	10.6	653	11.1
TP10	932	513	640	24.8	686	33.7	684	33.3
TP11	626	379	375	-1	365	-3.7	358	-5.5
TP12	895	572	564	-1.3	549	-3.9	530	-7.3

Note that it is impossible to achieve arbitrarily set target illuminance at all the test points simultaneously. For example, while at test points 5 and 6, the absolute deviation from the target increases during the iterations, at neighboring test point 4, the absolute deviation first goes down from iteration 1 to 2, and then increases slightly during iteration 3. But at all three test points, the illuminance increases from one iteration to the next. It is impossible to reach the target level at test point 4 without overshooting at test points 5 and 6, since the contribution from L-2 is greater at test points 5 and 6 than at test point 4. The dimming algorithm considers all test points simultaneously and tries to optimize the illuminance levels so that the overall error in reaching the target illuminance at all points can be minimized.

Table 7 gives the percent error in estimating initial illuminance, target illuminance and illuminance computed after each iteration at different test points. Since the camera has an approximate error of 13% in estimating the luminance (Sarkar 2005), an illuminance estimation error of at least 13% (not including other sources of error) is expected with the current test setup. An error above 13% has been highlighted in the table. Note that this error increases across the iterations at most points. A plausible explanation is that an increase in sensor temperature during the operation causes a change in the camera output. However this issue needs further investigation. Large errors at test point 1 demonstrate the necessity of a higher resolution camera to accurately estimate illuminance at distant points. Test point 2 gives a better result than test point 1 because of relatively higher illuminance (lower signal-to-noise ratio).

TABLE 7. Percent deviation in computed illuminance from the measured values after each iteration (significant errors highlighted in bold)



Test Point	**Initial E**	**Target E**	**Iteration-1**	**Iteration-2**	**Iteration-3**
TP1	**-28.4**	**-15.71**	**-22.64**	**-34.1**	**-38**
TP2	-2.8	2.43	**18.19**	-3.3	-11.9
TP3	**-13.2**	**-14.93**	3.71	**-15.5**	**-21.4**
TP4	-8.7	2.01	9.89	-5.2	-9.9
TP5	-9.7	0	3.34	-8.4	-11.2
TP6	-10.5	-0.28	2.42	-7.2	-12.3
TP7	-12.6	-0.13	-5.93	-12.4	**-15.1**
TP8	-1.1	**14.07**	8.94	2.9	1
TP9	-11.5	10.77	-5.56	-12.6	-10.9
TP10	**-16.6**	3	-11.98	**-18.2**	**-19.5**
TP11	-6.7	8.81	3.54	-7.3	-8.2
TP12	**-16.7**	-0.09	-8.79	**-15.8**	**-14.2**

To summarize, this test identifies some of the issues associated with proper calibration and operation of the system, and shows that there are opportunities for improvement of this system. The performance of the dimming algorithm and the overall system depends on the accuracy of its inputs, that is, the daylight level and individual luminaire contribution as determined by CamSensor. If the imaging system is capable of estimating the illuminance levels more accurately, even at low light levels, better system performance can be expected.

6 LIMITATIONS OF CAMSENSOR AND FUTURE WORK

Like any other new technology, CamSensor has its limitations. There is a certain amount of error associated with estimating luminance from a scene image, and also in deriving illuminance from luminance. The calibration procedure proposed here is not automatic, since user intervention is required in identifying the target points and in placing Lambertian surfaces at the target points.

There are some constraints regarding the location of such a system, as it must be placed in a position where specular reflections from daylight do not occur. One such position would be to locate the camera on the same wall as the daylight delivery system, looking away from daylight aperture. This location must have a view of all desired target points. An open office space with a low ceiling and cubicles is certainly not the ideal space for this application. A space with a high ceiling and considerable variation in daylight levels, requiring different target illuminance in different areas seems to be more appropriate for CamSensor.

Another potential serious issue is that of the desk surface being covered with objects like books and papers, or occupants blocking the view from camera. One probable solution will be to automatically replace the affected target points with nearby points that are unaltered. Comparing images of the present scene with the one taken during the calibration can help to detect target surface changes.

It is important that target points be located such that every luminaire has a strong contribution at one or more test points. Otherwise luminaires outside the dimming zone can potentially be dimmed to an unacceptable level, unless the software algorithm addresses these situations.

A thorough investigation is required on the imaging system itself. The type of sensor, the resolution of the camera and the measurement of the sensor spectral response function are all important considerations that require further study.
Integration of the hardware and software is needed to make the system fully automatic. Refinement and standardization of the calibration method is another area for further research.
This camera-based sensor can be applied to the vertical surfaces as well, and can be used to evaluate other lighting quality issues. Blind control can be integrated into CamSensor. In the realm of analytical research, an energy analysis will be critical to understand how the system can save energy over time, and how it performs compared to the conventional system as far as energy saving is concerned.

7 CONCLUSIONS

In this paper we have investigated the feasibility of using an inexpensive image sensor coupled with High Dynamic Range imaging technique to control electric lighting system. A calibration procedure to derive the illuminance at different test points from the workplane images is proposed. Analysis of the system performance in an experimental setup leads to the following conclusions:

1. Camera sensing technology appears to be a feasible method for lighting control with DALI equipment.
2. Surface reflectance properties create the need to calibrate the control system for different light sources for the conversion of luminance to illuminance.
3. Low resolution cameras may have more difficulty dealing with distant surfaces, particularly when the illuminance is low.
4. Proper system layout is necessary for the coordination between luminaires and the target points.
5. A target level may not always permit excellent agreement at all target points.

The strength of CamSensor lies in the fact that it can take full advantage of the available digital technologies, including a digital imaging system and digitally controlled ballasts. As digital technologies continue to gain momentum in all spheres of life, the need of an advanced daylight sensing is imminent. Further research on CamSensor can provide a lead to the next-generation daylight sensing technology.

REFERENCES

[DALI-AG] Digital Addressable Lighting Interface Activity Group. 2001. DALI Manual. Frankfurt, Germany. 62 p.

Debevec PE, Malik J. 1997. Recovering High Dynamic Range radiance maps from photographs.

ACM SIGGRAPH Proceedings of the 24th annual conference on computer graphics and interactive techniques.

Glennie WL, Thukral I, Rea MS. 1992. Lighting Control: feasibility demonstration of a new type of system. Lighting Research and Technology 24(4): 235-242.

Kim S and Mistrick R. 2001. Recommended daylight conditions for photosensor system calibration in a small office. J Illum Eng Soc. 30(2): 176-188.

Mistrick RG and Thongtipaya J. 1997. Analysis of daylight photocell placement and view in a small office. J Illum Eng Soc. 26(2): 150-160

Mistrick R and Sarkar A. 2005. A study of daylight-responsive photosensor control in five daylighted classrooms. J Illum Eng Soc. 2(1): 51-74.

[NLPIP] National Lighting Product Information Program. 1998. Specifier reports: photosensors. 6(1).

Omnivision Technologies Inc. 2001 July 10. OV7620 single-chip CMOS VGA color digital camera product specification. Version 2.1. Sunnyvale (California). 58 p.

Rubinstein F, Jennings J, Avery D, Blanc S. 1999. Preliminary results from an advanced lighting controls testbed, J Illum Eng Soc. 28: 130-141.

Sarkar A. 2005. Proof-of-concept: CMOS sensor based lighting control system integrating high dynamic range imaging and DALI [dissertation]. University Park, Pennsylvania: Pennsylvania State University. 167 p.