Integrated Daylight Harvesting and Occupancy Detection Using Digital Imaging

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ABSTRACT

This paper describes a proof-of-concept implementation that uses a high dynamic range CMOS video camera to integrate daylight harvesting and occupancy sensing functionalities. It has been demonstrated that the proposed concept not only circumvents several drawbacks of conventional lighting control sensors, but also offers functionalities that are not currently achievable by these sensors. The prototype involves three algorithms, daylight estimation, occupancy detection and lighting control. The calibrated system directly estimates luminance from digital images of the occupied room for use in the daylight estimation algorithm. A novel occupancy detection algorithm involving color processing in YCC space has been developed. Our lighting control algorithm is based on the least squares technique. Results of a daylong pilot test show that the system i) can meet different target light-level requirements for different task areas within the field-of-view of the sensor, ii) is unaffected by direct sunlight or a direct view of a light source, iii) detects very small movements within the room, and iv) allows real-time energy monitoring and performance analysis. A discussion of the drawbacks of the current prototype is included along with the technological challenges that will be addressed in the next phase of our research.

Keywords: Lighting control, photosensors, occupancy sensors, High Dynamic Range (HDR), Digital Addressable Lighting Interface (DALI), CMOS video camera, digital color imaging

1. INTRODUCTION

California, the world's fifth largest economy, uses 265,000 GWh of energy each year, with peak demand growing annually at about 2.4%.[1] Total commercial electric consumption amounts to 67,707 GWh annually.[2] Nationally, the building sector's energy consumption is expected to increase by 35% between now and 2025, while commercial energy demand grows at an average annual projected rate of 4.7×10^{14} Wh.[3] In fact, commercial buildings consume 18% of the nation's annual energy use, and 35% of the nation's total electricity.[4]

Previous research has shown that lighting comprises 20% - 40% of total electric power consumed in commercial buildings.[5] Using California as an example, interior lighting is the highest primary electric end use (29%) as well as the highest overall annual end-use electric intensity (3.92 kWh/ft^2).[2] Lighting in the commercial office spaces alone consumes 4,997 GWh annually and accounts for 33% (5300 MW) of commercial peak demand.[6] A review of building load databases has indicated that on an average, peak demand charges account for roughly 40% of total electricity expenditures and a 1% reduction in peak demand reduces annual electricity expenditures by 0.4%.[4]

An effective way to address this energy problem is to deploy automatic lighting control systems. Automatic lighting controls are capable of reducing energy consumption by up to 50% in existing buildings (in the case of an electronically ballasted lighting control system in an office building in San Francisco)[7] and by 35% in new constructions.[8] However, conventional lighting control technologies, partly due to their various technological drawbacks, have traditionally faced market barriers, leading to lower market penetration than some other building technologies.

We believe any future market transformation in lighting control will be propelled by novel lighting control technologies that will overcome the drawbacks of conventional systems and demonstrate superior performance than what is currently feasible. This is the motivation behind this ongoing research.

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In the first phase, methods and algorithms were developed for daylight harvesting using digital imaging technology.[9,10] In this paper, we report the results of a 4-month long proof-of-concept research we recently completed at RIT. As part of this research, we developed a preliminary functional prototype, described hereafter as CamSensor-2 or CS-2, which integrates daylight harvesting and occupancy sensing into a single automatic lighting control system.

2. BACKGROUND

2.1. Occupancy sensors and their drawbacks

With typical energy savings ranging from 52% - 58% for classrooms and 28%-38% for private offices,[11] occupancy sensors are often viewed as one of the most energy and cost-effective lighting control technologies. However, even after being around for over 20 years, occupancy sensors do not have as high market penetration as some other building technologies (less than 10% commercial floor space served nationally[4]), partly due to the difficulty in definitively predicting and demonstrating savings. Occupancy sensor performance is also dependent on the user occupancy, lighting control patterns, sensor selection and finally, commissioning, leading to varied savings estimates by the industry.[12] Recent research has shown that reducing the time delay in the occupancy sensors can increase the energy savings in spite of a potential increase in lamp maintenance cost due to higher switching frequency. [11] It has been found that the activity level is different for different users of a common space and even changes over the time of the day for a given user.[13] However, a typical occupancy sensor only allows a single time delay setting based on the application, which can vary from several seconds to more than 30 minutes, and remains constant once set. The time delay is commonly maintained at a higher level than necessary to minimize false offs (when no motion is detected in presence of occupancy), thus reducing energy savings. Once calibrated, the sensitivity of the device to room movement cannot be changed as well. Most occupancy sensors used in commercial applications use passive infrared or ultrasonic motion-sensing technologies. Many use dual technologies, which combine the two technologies or others, such as microwave, in one sensor.[14]

2.2. PhotoSensors and their drawbacks

In comparison to occupancy detection, daylight harvesting is a significantly less successful and somewhat less popular lighting control strategy. The use of photosensors to control interior lighting is nontrivial. Since a photosensor signal greatly depends on the position of the sensor relative to room surfaces and daylight apertures, as well as 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 market barriers.[15-19]

Further, a new paradigm in lighting control has started with the introduction of digital, addressable ballasts. Dimming of individual ballasts permits such a lighting control system to achieve different electric light output levels across a space, providing more flexibility and precise control of the illuminated environment. Digital Addressable Lighting Interface (DALI) is one such technology.[20] Very recently, DALI has been used in a major field study of the performance of automated roller shades and daylight controls in a mockup of the daylighting system in The New York Times Headquarters.[3] DALI continues to mature as a technology with increased affordability ($30-$75 per ballast[3]), while other digital technologies continue to gain ground. Thus, there is a need for an advanced daylight sensor that can reap the benefits and flexibility that these technologies offer and achieve a better control of the light distribution within a space, improving the overall light quality.

2.3. An image sensor

An image sensor can be thought of as a cluster of photosensors. Unlike photosensors, they do not give us a single electrical signal, but rather provide luminance as well as color information at thousands of points within the space. A sequence of digital images of the space thus gives us a wealth of information that we can use to estimate daylight availability in various parts of the space simultaneously, as well as detect occupancy. Thanks to the tremendous growth and development in CMOS technology, today digital imaging is pervading every sphere of our life, providing us with cost-effective and innovative solutions.

Recently, high dynamic range CMOS video sensors have been introduced in the market, primarily for various automotive applications,[21,22] whose technical constraints are somewhat similar to those of interior lighting applications. In both cases, the imaging system needs to work under a wide dynamic range, have a fast (more time critical in some real-time automotive applications) but affordable image processing functionality, and finally, have integrated image acquisition and image processing modules that continuously interact with each other.[23] Real-time operation might involve adjusting the image acquisition system based on the lighting condition. However, the lighting product will have a more stringent budget constraint than a product for an automotive application. Here, by automotive applications we mean lane recognition, parking control, obstacle/traffic sign recognition etc.

2.4. Proposed concept: an integrated lighting control sensor

The fundamental hypothesis of this research is that we can use an image sensor for daylight harvesting and occupancy sensing at the same time, but more importantly, for developing a lighting control system that is more versatile and that offers a far better control of the illuminated environment. Our approach is significantly different from the prior image sensor based lighting control devices envisioned by other researchers.[24-26] We demonstrate that several drawbacks of conventional lighting control sensors can be circumvented by the proposed concept. In addition, an integrated sensor can provide functionalities that are impossible to achieve by conventional photosensors and occupancy sensors. Some of these features have already been implemented in the current work.

Following are some advantages offered by the proposed solution over conventional systems:

- A single sensor can function as a photosensor as well as an occupancy sensor
- A single sensor can be used for different task areas (or control zones) with different target light level requirements, as long as the sensor has a view of all task areas. A conventional system will typically need several photosensors for this purpose
- Compared to a conventional photosensor, the performance of the proposed system is far less likely to be adversely affected by a direct view of a light source or direct sunlight
- The sensor is capable of detecting small movements, on the order of a couple of inches, several feet away from the camera as long as it has an adequate resolution. The sensor sensitivity to motion can be adjusted in real-time based on the activity level or other criteria. As such, this approach can offer a better capability in occupancy detection compared to conventional occupancy sensors
- Algorithms can be developed so that the problem of people or objects partially blocking the sensor's view of the task areas can be circumvented (not implemented in CS-2)
- Real-time energy monitoring and performance analysis of the actual system is possible, which is unique to this application
- Image processing techniques can be employed to achieve enhanced functionalities like automatic calibration and detecting areas for selective scanning of the scene to ensure low response time (not implemented in CS-2)
- CMOS technology can provide an attractive and cost effective solution (cost analysis has not been conducted for CS-2)

We envision the proposed solution to neither have a video recording/storage capability, nor have an appearance of a typical camera. This should overcome any privacy concerns potential customers might have.

3. TECHNICAL DETAILS OF THE PROTOTYPE

3.1. Hardware

The main component of CS-2 is a color XAECK100 Automotive Evaluation Kit based on SMaL camera technology from Cypress Semiconductor Corp (now owned by Sensata Technologies).[27] The kit consists of an imager module (or camera head), an FPGA Processing Box and SMaL image capture Application Programming Interface (API).

The imager is a CMOS sensor with the following specifications: i) high dynamic range up to 120 dB, ii) a resolution of 640x480 pixels, iii) 8 or 12 bit image capture modes, iv) up to 60 fps variable frame rate, v) progressive scan mode with rolling shutter, vi) a spectral range of 400-1100 nm, vii) 45 dB digital signal-to-noise ratio, viii) 0.09% fixed pattern noise, and ix) 5V/lux sec sensitivity. We used the standard 1/3" C-Mount lens with a nominal field-of-view of 50°. The electronics in the camera head transports the digital sensor data to the processing box through Low Voltage Differential Signaling (LVDS) serial interface (CAT-5 cable).

The Processing Box contains a 2 million Gate Xilinx FPGA video controller board, which is connected to a PC through a IEEE 1394/Firewire interface. The controller includes various image processing features like dark current removal, column fixed pattern noise correction, defective pixel correction, 3x3 general sharpening etc. It also allows automatic and manual control of the integration period and the dynamic range. The dynamic range can be controlled by selecting one of 29 pre-defined response (or gamma) curves. All image processing features and parameters are programmable and can be manually controlled by setting the appropriate registers in the FPGA. This is accomplished by the virtual addressing mechanism implemented in the image capture API. All automatic processing features like white balance, autoexposure, Automatic Gain Control (AGC) and gamma control were disabled by modifying appropriate registers. Obtaining raw image data is important for this application.

It must be pointed out that the above specifications are not the recommended configuration for this application, but merely the configuration of the hardware available for this work. Determining the minimum system requirement or a cost analysis was out of the scope in this phase of our research.

CS-2 also includes a Digital Addressable Lighting Interface (DALI) controller that helps control the DALI dimming ballasts by sending digital commands from the computer to individually addressed ballasts. The controller has an RS-232 serial interface and follows DALI communication protocol.[20] The master control of CS-2 was a windows-based computer with modest hardware configuration (1.8 GHz, 512 MB RAM, WinXP).

3.2. Daylight-sensing with CS-2

The camera was calibrated to generate the response curves for the three channels so that luminance (in cd/m^2) could be estimated directly from the digital counts. A brief description of the calibration process follows.

A Colorchecker DC color chart and a gray card were imaged by the camera. Only the grayscale patches in the colorchecker were used in this calibration. The gray card data was used to correct for the spatial non-uniformity of lighting. Three different exposure settings were used to ensure proper sampling of the full 8-bit range.

A sample of Halon (Polytetrafluoroethylene or PTFE) was placed near the chart before the image capture. Halon has a spectral reflectance factor close to unity with very high spatial uniformity and is nonselective across wavelengths. Thus, it is used as a perfect reflecting diffuser (PRD). Absolute luminance (in cd/m^2) of the brightest patch in the colorchecker and the spectral reflectance of the PRD were measured using a spectroradiometer. Now, the spectral reflectance of each gray patch being known, CIE tristimulus value Y was computed for each patch using Eq (1).

$$Y = k\sum_{\lambda} S_\lambda R_\lambda \bar{y}_\lambda \Delta\lambda$$
$$k = \frac{100}{\sum_{\lambda} S_\lambda \bar{y}_\lambda \Delta\lambda} \tag{1}$$

Where S_λ is a spectral power distribution of the light source (obtained from the spectral reflectance data of the PRD), R_λ is the object's spectral reflectance factor, y is the CIE 10° standard observer color matching function and k is a normalizing constant. X and Z tristimulus values can be found similarly. The summation is performed over the wavelength range of 380-780 nm at 10 nm intervals. Eq (1) can also be used to compute Y_n, tristimulus value of the light source, assuming $R_\lambda = 1$ for the PRD. To obtain the absolute luminance values, normalized Y values of each patch were multiplied by the measured absolute luminance of the white patch. Figure 1 shows the calibration measurement and the response curves for the three channels. In this case, only the green channel response was used for obtaining absolute luminance. Note that the hardware takes care of the dark current correction. A digital count of zero corresponds to 0.75 cd/m^2 and a maximum digital count of 255 corresponds to 91 cd/m^2.

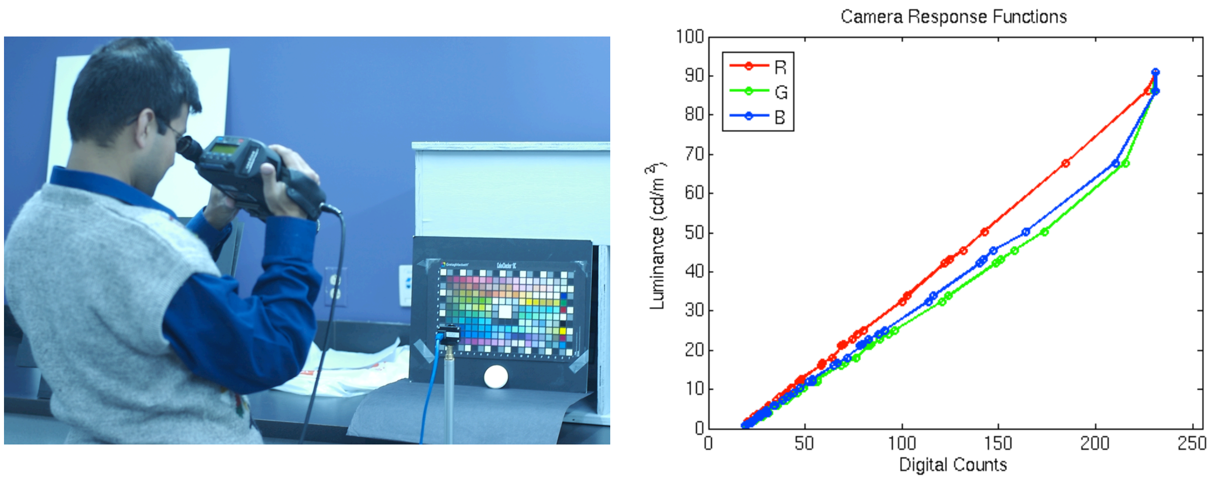

Fig.1. Calibration to determine response functions for the three channels of the video camera

Luminance is used throughout the daylight-sensing algorithm. Current and target light levels were determined by estimating luminance values from digital images of the space under present and ideal lighting scenarios respectively. This, although an approximate method, avoids the complicated calibration process to estimate illuminance from luminance as proposed earlier.[10] It is important to avoid specular reflection due to daylight coming from a task area by positioning the camera appropriately. Contributions from individual fixtures were determined during nighttime calibration. A lighting control algorithm was implemented to determine the dimming levels of individual fixtures required to reach the target light levels for different task areas simultaneously based on the daylight contribution. Details of the algorithm have been published earlier.[10] The algorithm, based on least squares technique, tries to minimize the difference between target and current light levels for all task areas simultaneously. This is one of the most important advantages of this application. Please note that instead of absolute luminance, relative luminance can also be used for daylight sensing.

3.3. Occupancy sensing with CS-2

Our occupancy detection algorithm uses digital color imaging technique. The algorithm, based on reference image method, uses YCC color space instead of RGB. YCC values were obtained using Eq (2).[28]

$$\begin{bmatrix} Y \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.168736 & -0.331264 & 0.5 \\ 0.5 & -0.418688 & -0.081312 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{2}$$

First, absolute YCC image difference between the last frame and the current frame is computed. The last two components of YCC contain chromatic information independent of the intensity. These are used to derive an rms difference metric as per Eq (3).

$$rms = \sqrt{\left(C_{b2} - C_{b1}\right)^2 + \left(C_{r2} - C_{r1}\right)^2} \tag{3}$$

Where, (C_{b1}, C_{r1}) are the chromatic components at a given pixel in the last frame, and (C_{b2}, C_{r2}) are the corresponding values in the current frame. The metric is simply the Euclidean distance in the C_b - C_r plane. The difference image (pixel differences between any frame and the reference frame) and the thresholds are based on this metric. There are two user-specified thresholds, one for the pixel difference, and one for the spatial extent (in terms of a fraction of total number of pixels in a frame). These thresholds are programmable, thus allowing a real-time adjustment to the motion sensitivity of the sensor based on the operating requirements. The detection area is controlled through the specification of regions of interests, otherwise the whole frame is considered.

There are three advantages of using such an approach. Firstly, since YCC data format is very common in video processing, additional transformations may not be needed if YCC format is used throughout the processing chain.

Secondly, the detection of changes between frames is more robust against pixel noise. The pixel noise is likely to be introduced during various stages of the processing chain, including compression and transmission, and is predominantly present in the intensity channel. This metric is also less likely to be seriously affected by minor changes in the space illumination level than a metric based on raw RGB values. This is convenient because a change in the light level in the space does not typically cause a false alarm, unless the change is significant. Finally, this method is fast and inexpensive, which is a critical requirement for this application.

Preliminary test showed CS-2 could detect very small head movement, on the order of 3-5 inches from a distance of 10 feet. However, occupancy detection under low light level was not very satisfactory. This is unlikely to be a hardware limitation, as the sensor works at a luminance as low as 0.88 cd/m^2.[29] One probable cause for this problem is that our occupancy detection method uses only the chromatic information in the image, and at low light levels, there is not much chromatic information present in the scene. The occupancy detection method needs to be more robust at low light levels as well as in rapidly changing daylight situations. Considering connected regions during occupancy detection may help in differentiating between daylight change and human motion. The performance of the occupancy detection algorithm could not be thoroughly evaluated because of a software constraint described below. Nonetheless, the initial results are promising.

3.4. CS-2 software

CS-2 software contains three modules developed in various programming environment. The code and algorithm for the Image Acquisition Module was developed in C++, built around the SMaL Image Capture API. The Processing Module, containing the daylight sensing, occupancy detection and lighting control algorithms as well as the graphical user interface, were developed in Matlab. The code for the DALI Communication Module was written in C. The operation of these modules is synchronized by updating parameter values in configuration files, which imposes a constraint on the system response and operating speed. The system performance should significantly improve under an integrated development environment.

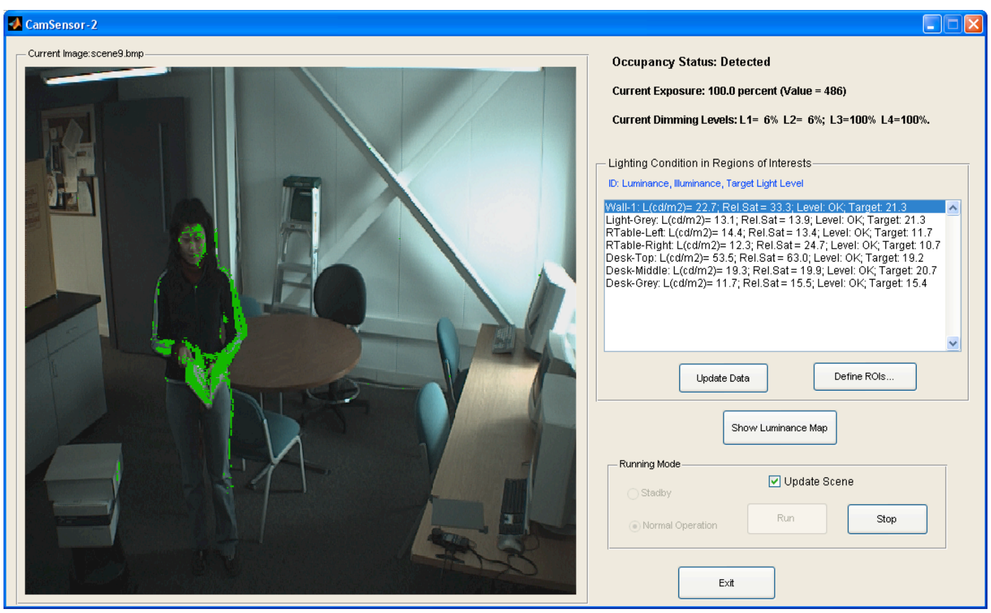

Fig.2. Graphical User Interface for the CS-2 Software

The image acquisition module in CS-2 configures the imager and then runs in a continuous loop, in which it captures and stores 10 frames in pre-defined time intervals and overwrites them in the next cycle. If the Processing Module does not detect occupancy for a given amount of time, the system goes to standby mode where daylight dimming is not operational. Normal operation is resumed only when the thresholds discussed earlier are exceeded multiple times in successive frames. This reduces the probability of false alarms. It is critical that the system response time is minimized in the standby mode, so that it can react to occupancy detection within a fraction of a second. This underlines the importance of having a fast and efficient occupancy detection algorithm. The timing aspect could not be properly tested in CS-2 because of the software constraint described above.

As the CS-2 software detects motion, it is highlighted on the image in green (Figure 2). During the system setup/commissioning process, the software allows the user to specify different regions of interest (ROI) where different target light levels need to be maintained. The software adjusts the camera exposure in real-time until the light levels in each ROI can be properly estimated. If needed, the exposure is adjusted for one ROI at a time. This ensures that local glare does not cause system malfunction. After resuming normal mode operation or after the exposure is updated, adequate wait time is allowed for the lighting condition and/or the imaging system to stabilize.

4. A PILOT TEST OF CS-2

CS-2 prototype was run continuously for 4-6 hours on three separate occasions to evaluate the daylight sensing and lighting control functionalities. Results presented here are from one of these tests conducted from 12 noon to 4 PM on February 24, 2006, which was a partly sunny day in Rochester, NY.

Four bare strip lights (F32-T8) with DALI ballasts were fitted into a room with adequate daylight. Figure 3 shows views of the room with the complete setup. The setup included several non-dimmable recessed troffers. Each troffer had three F40-T12 lamps, with the middle lamp on a separate circuit from the outer ones. These fixtures were turned on or off to simulate different lighting conditions inside the room. All lamps had a color temperature of 6500K. The camera was installed at one corner, looking away from the windows, but with a direct view of a bare lamp. Window blind positions were changed from time to time to simulate different daylight conditions.

Fig.3. Experimental Setup

Figure 4 shows the seven Regions of Interests (ROIs) used in this experiment. To give an idea about the locations of the dimmable fixtures, L1 is almost right above ROI-5, L2 (visible in Figure 4) is closest to ROI-3, L3 is very close to ROI-7 and L4 is right above ROI-2. The ROIs were dispersed throughout the room and covered areas with varied surface reflectance. For example, ROI-1 was on the white wall and was at times partially covered with a black cardboard, ROI-2 was on a gray paper with close to 30% reflectance, ROI-3 and ROI-4 were on a round table with low surface reflectance, ROI-5 and ROI-6 were on another table with higher reflectance, and lastly, ROI-7 was on a 18% gray card. Thus, the luminance values corresponding to these ROIs varied widely during the experiment. It is, however, unlikely in a real-life application that task areas so close to each other will have different illumination requirements. Daylight and electric light availability varied quite drastically from one ROI to the other, making it a somewhat challenging application in terms of lighting control. This test setup was for demonstration purposes only. Large commercial spaces will likely have multiple control zones with various illumination requirements. Each ROI can be treated as a control zone in this application.

Every two minutes, all the data at each of the seven ROIs were recorded and automatically logged, including the illuminance measured by a luxmeter at a point close to the gray card (ROI-7). Since the gray card was fairly diffuse, the ratio of illuminance to luminance was assumed to be constant and independent of the direction of incident light. Thus measuring the illuminance on the gray card would give an indication as to how well the daylight could be estimated by CS-2 in case of diffuse surfaces. In presence of specular reflection, the relationship between illuminance and luminance is directional, resulting in a potential error in estimating illuminance from luminance. Images were saved at the same time the data were recorded. This allows us to do a detailed performance analysis and monitoring (and possibly system diagnosis).

The high dynamic range of the sensor and software controlled exposure allowed the system to operate normally even in the presence of direct sunlight and with a bare fluorescent lamp in the field-of-view, as shown in Figure 5. Both these conditions are likely to be problematic for conventional photosensors.

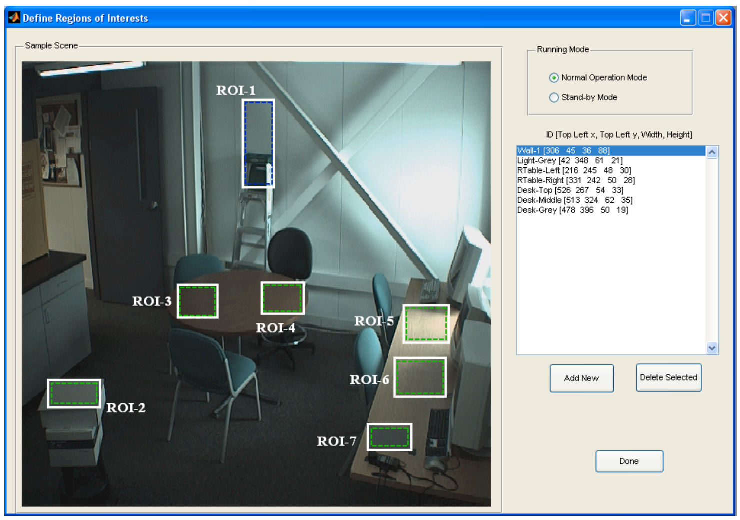

Fig.4. A screen-shot of the window with ROIs marked and labeled

Fig.5. System functionality is not affected by a view of direct sunlight patches and a bare lamp

5. RESULTS AND ANALYSIS

This section contains a brief discussion on the results obtained from the pilot test. A detailed performance analysis is beyond the scope of this paper.

Figure 6 shows the variation in estimated luminance for different ROIs over time. Target luminance levels are plotted as dotted lines. Abrupt rises and falls in the graphs show the times when the blinds were operated to drastically change the daylight entering the room. However for ROI-1, the changes during 65th and 85th measurements were due to the black cardboard being removed and reintroduced respectively. A general tendency for most graphs is to slowly move toward the target light levels over time. Note different scales for different ROIs. Note that target light levels cannot possibly be achieved for all ROIs. For example, ROI-5 and ROI-6 were quite close to the window and so had a high illumination level most of the time. ROI-2 received a strong daylight contribution from around 20th measurement through the 65th measurement, which caused the luminance level to far exceed the target level during this time. Toward the end, the luminance levels fell below the target levels for most ROIs because of inadequate daylight, but having a luminance on ROI-5 close to the target level prevented a rapid correction for other ROIs. As mentioned before, the least squares technique in the lighting control algorithm tries to minimize the difference between target and current light levels for all ROIs simultaneously. Rapid and abrupt change in the dimming levels is avoided by the algorithms, as evident in the graphs.

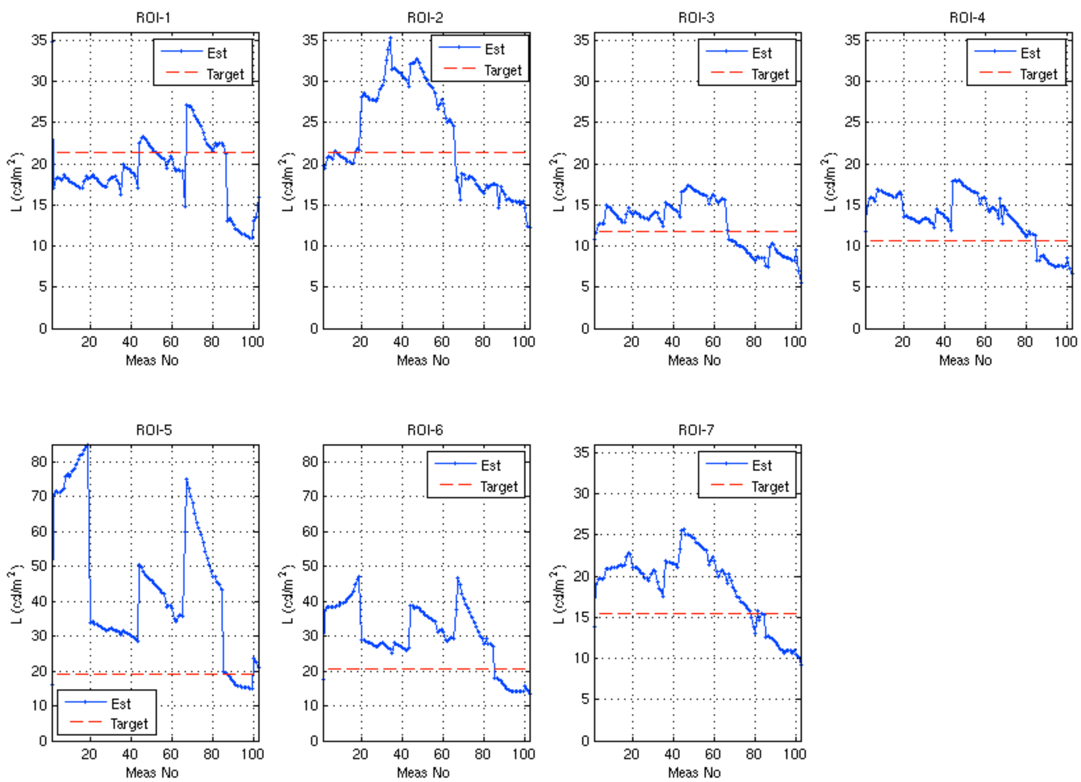

Fig.6. Light level (luminance) variation in different Regions of Interests

Figure 7 shows the dimming level variation for individual fixtures. This illustrates how the system responded to changes in daylight availability within the room. The fixture L1 was the closest to ROI-5, which had a high illumination level due to its proximity to the window. So for the most part, L1 was dimmed to 1%. L4 was right above ROI-2, which received direct sunlight between the 20th and the 65th measurements. During this time, L4 was dimmed to 1% as well. L3 and L4 were not set at full output at the same time, as that would exceed the target illuminations for ROI-2 and ROI-7. On the other hand, with L1 being dimmed to 1%, L2 was mainly responsible for providing adequate illumination to ROI-1 and ROI-3. L2 was kept at 100% for the most part. While the luminance level at ROI-3 exceeded the target because of L2, ROI-1 was below the target level for the most part, but in both cases, the deviation was not large. This shows that CS-2 performed reasonably well in addressing different daylight requirements of various regions, based on the luminance information available. Figure 7 also illustrates that real-time energy monitoring and performance analysis can be achieved in this application. In this particular test, the average dimming levels for the four fixtures were 8%, 80%, 69% and 26% respectively, and average power savings were 54%.

Figure 8 shows plots of target illuminance (in lux) for ROI-7 and the illuminance measured by the luxmeter. There was a significant deviation at times from the target illuminance. Abrupt increase in the illuminance level was caused by opening the blinds. Illuminance level started reducing slowly after each such increase. During the 65th measurement, there was an abrupt drop. Around the same time, the daylight contribution to ROI-5 and ROI-6 increased markedly (Figure 6), resulting in high luminance values. CS-2 responded by dimming L2 and L3 to 1%, which resulted in the drop in ROI-7's illuminance level. From the 65th through the 80th measurements, for about 30 minutes, CS-2 allowed this illuminance to fall further as the daylight contribution reduced, before increasing the light output of L3. Between the 85th and the 100th measurements, available daylight started reducing rapidly (between 3:30 PM and 4 PM). For all ROIs, the luminance levels were below the targets, and falling further. CS-2 responded by changing L2 output level from 1% to 100%, and slowly increasing L1 and L4 output levels. The performance probably would have been better had ROI-5 not have a strong daylight contribution. Assigning priority levels to various ROIs in the lighting control algorithm may address this problem.

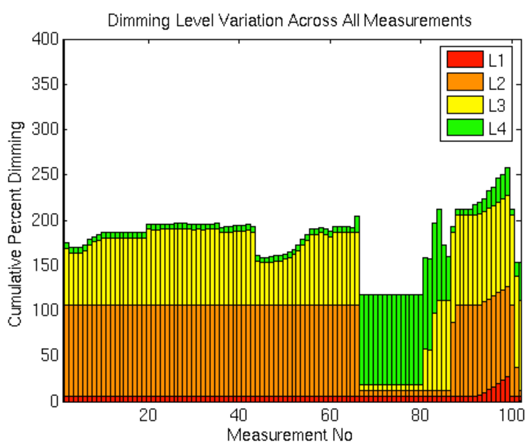

Fig.7. Dimming level variation for each fixture over time

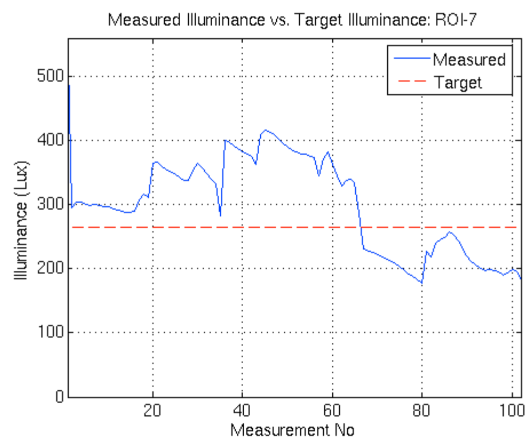

Fig.8. Target and measured illuminance (in lux) near ROI-7 as measured by the luxmeter

Considering wide changes in the daylight availability within the room, the performance of CS-2 seems acceptable. Precise daylight control is neither expected, nor achievable by any lighting control system in real-life applications. That said, a thorough performance analysis would require measuring the illuminance levels for each of the ROIs, and quantifying the accuracy of the daylight estimation method with luminance as the lighting metric. Neither of these could be undertaken because of time and resource limitations.

6. CONCLUSIONS

In this paper, we discussed a proof-of-concept implementation that uses a high dynamic range CMOS video sensor to integrate daylight harvesting and occupancy sensing functionalities into a single automatic lighting control system. We described a preliminary functional prototype, named CamSensor-2 or CS-2, which we developed during our research. We also proposed a fast and inexpensive occupancy sensing method suitable for this application.

Future research on CamSensor must focus on customizing the image sensor and the hardware, with the application requirements and commercial viability of the concept in mind. The emphasis should be on making the system stand-alone, capable of functioning with or without a workstation. It should also be possible to interface the system with a standard lighting control panel. System setup (or commissioning) procedure needs to be further simplified to enable stand-alone operation, minimizing user intervention even further. An embedded system approach is foreseen. The software requirements will be governed by the hardware capability of the system, which in turn will be governed by its commercial viability. Cost-effectiveness will be a prime concern in future works in order to make this approach attractive to the lighting control market.

Following technical feasibility issues need to be investigated in any future work on this application:

1. *Occupancy detection requirements:* Fast detection with minimal time lag to trigger, detection at very low light level, high coverage area with optimal sensor resolution, high sensitivity.
2. *Estimating task illuminance from pixel data:* Specular reflection from daylight can cause the prototype to overestimate illuminance in localized areas. To counter this, existing algorithm needs to be improved and a suitable calibration and commissioning procedure must be outlined.
3. *Estimating task illuminance on movable desks:* In a typical classroom, the desks can be moved during the day, a scenario that requires a different calibration process than the current one. An image processing algorithm that considers different segments of a space during automatic nighttime calibration can be developed so that even when desks are moved from one region to the other, approximate task illuminance can still be estimated.
4. *Estimating task illuminance for dark surfaces:* Dark surfaces will typically have low luminance, thus signal-to-noise ratio becomes an issue in estimating task illuminance on dark surfaces.
5. *Meeting industry expectation on cost:* The most important technical challenge will be to develop a cost-competitive scalable solution without compromising the performance.

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