A low cost sky-scanning device as centralized sensor for real-time light control in building management application

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Abstract: A low-cost LDR-based angular sky-luminance measurement device is proposed as a centralized sensor for predicting real-time illuminance distribution in building interiors over a wide district, for application in centralized light control.

1. Introduction

Daylight is essential to human health and productivity[1], and enhancing daylight infiltration in building interiors through design optimization serves the additional purpose of reducing requirements of complementary electric space lighting while maintaining pre-defined indoor illuminance levels. Of the three components of daylight — the sky component, internally reflected component, and externally reflected component — the sky-component is the actual source and has a dynamic behavior owing to seasonal and diurnal change in sun's position in the sky-hemisphere, and the variation in scattering phenomenon and sky-turbidity on a dynamic basis. Daylight illuminance at any point indoors is due to the luminance of the sky positions "as seen" from that point, as such it is important to quantify sky-luminance at discrete positions on a dynamic basis. Here, the assumption is that Sun is also part of the sky-hemisphere, and the circumsolar region of the sky is always highly luminous as compared to other regions of the hemisphere. Sky models can be used to generate spatially discretized sky-luminance datasets for indoor illuminance calculations; however, generic application of the standard sky models for all time-points can underestimate the actual indoor illuminance distribution.

Light control in a facility requires light-intensity sensors at points of interest, and in this study, we propose a strategy using 'virtual sensors' in a real-time simulation. Light intensity sensors, real or virtual, can help in controlling electric lights to complement available daylight for maintaining desired illuminance at defined positions in the interiors. The "virtual sensors" are the points of interest in computational calculations, and their spot-illuminance is a factor of the sky-patch luminance as seen through the window at those points[2] as:

$$I_{net,a,b} = \sum_{\gamma\alpha} D_{\gamma\alpha} L_{\gamma\alpha} \Delta S_{\gamma\alpha} \qquad (1)$$

Here, the net illuminance (I_{net}) at point (a,b) in a room due to the sky-component from a window depends on the discretized luminance $L_{\gamma\alpha}$ from each patch of defined solid angle (ΔS), constrained between the azimuthal (α) and altitudinal (γ) boundaries of the window. Here, the daylight coefficient $D_{\gamma\alpha}$ depends on window geometry, room geometry, window transmittance, surface reflectance inside the room and external surroundings, but it is independent of sky luminance distribution $L_{\gamma\alpha}$. In terms of sky-geometry, the calculations for indoor illuminance at a point in the room through summing all discrete elements in the window may be presented[3] as in Eq. 2.

$$I_{net} = \sum_{i=0}^{N_\alpha} \sum_{j=0}^{N_\gamma} L_{\gamma_j \alpha_i} * sin\,(\gamma_j) * cos(\gamma_j) * cos(\alpha_{w_i}) * \Delta_\gamma \Delta_\alpha \qquad (2)$$

Here, 'i' and 'j' are the discrete elements of the window in azimuthal and altitudinal directions, respectively, when a window element of dimensions $\Delta_\alpha.\Delta_\gamma$ allows infiltration of daylight from sky-patch at angles (α, γ) — the calculations are simplified for a window cavity by neglecting angular transmissivity coefficient of window material, and assuming it unity for all angles. Also, the internally-reflected and externally-reflected components of daylight are neglected for simplifying calculations, by assuming maximum sky-exposure through minimal obstructions.

2. Materials and Method

It is important to identify the sky-luminance distribution in real time. Commercially available devices used for sky-luminance modeling studies[4]–[6] are costly[1] and this paper discusses an improved design of our previously reported low-cost light dependent resistor (LDR)-based device [7], [8] for application in indoor luminance measurement and light control. Using calibrated LDRs and open-source microcontroller, we had reported a 1/200

[1] EKO MS-321LR quoted at about USD 37,500 including landing charges and taxes in July 2017

times cost reduction as compared to commercial device[8], and the proposed modified design is a light-weight portable upgrade of our previous design — using Fresnel-like mounts for sensors, replacing the heavy circular frame — and costs about 1/600 the quoted cost of commercial device. Fig.1(a) demonstrates the concept of using Fresnel-frame to replace circular frame for mounting sensors at various altitudingal positions, and Fig. 1(b) demonstrates various perspectives and scan-motion of the device.

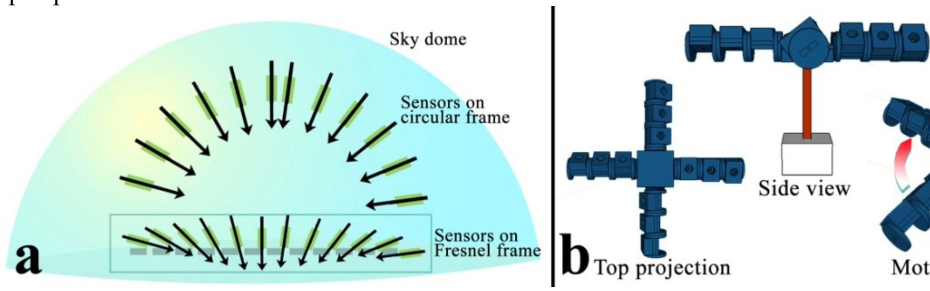

Fig. 1: (a) Sky scanner with circular and Fresnel-like frames for measuring sky-luminance distribution under the sky-dome, (b) various perspective views of the discussed sky-scanning apparatus.

The discretized sky-measurement is done by rotating the device in a vertical sweep, aligning through 24 azimuthal positions of step-size 15° each. The 12 sensors oriented with 7.5° degree altitudinal interval sequentially measure incident illuminance at each azimuthal position, thus creating a dataset of 265 sky positions (11 altitudinal x 24 azimuthal + zenith) each scan. The field of view is 11° for each calibrated sensor.

3. Experimental data and analysis

The device scans the sky in 5-minute interval, and generates an array of measured sky-luminance dataset. These datasets arranged in cylindrical-coordinate system are transformed into polar-coordinates to generate ambient sky-maps, as demonstrated in Figure 2a (representative images for 2-hour interval between 07:30h to 17:30h on 4th April 2018 at Mumbai, India). For a room with defined floor-plan and window dimensions, an algorithm scripted in Python (based on equations 2) is used to calculate the illuminance at all discrete points in the interiors. Figure 2b and 2c present the indoor illuminance calculated from the sky-component of daylight, when the principle window is oriented due-south and due-north respectively. In these calculations, room dimensions were 16x16 units, window dimensions were 4x4 units, and the window was placed 3 units above floor, equidistant from each wall.

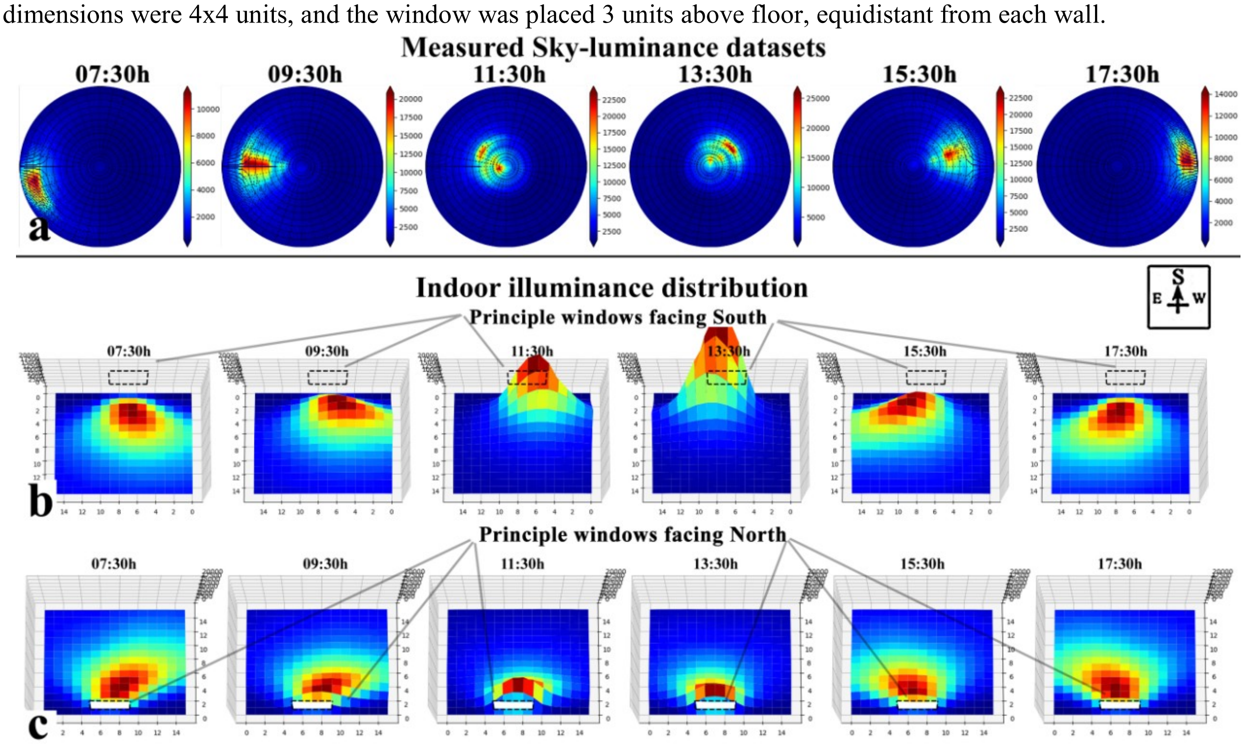

Fig. 2: (a) Sky-maps generated through polar coordinate transformation of measured sky-luminance datasets. (b, c) Indoor illuminance distribution calculated for principle window oriented due-south and due-north, respectively.

These calculations may be done in real-time for multiple facilities with defined dimensions of floor-plan and principle window, by using measured sky-luminance distribution datasets. When simulated with tabulated annual datasets, the results can help optimize the building design for maximum useful daylight infiltration. However, in building management systems, the measurement based predictions can help in controlling light-fixtures (switching/dimming) without the need of actual sensors placed at various points of interest in each facility; simulations can be run to identify illuminance at previously described 'virtual sensors'— predefined points of interest — for calculating illuminance on dynamic basis. Fig. 3(a) presents few representative points of interest in a room of previously described dimensions, with the principle window oriented south. Fig. 3(b) presents the illuminance calculated for the six points-of-interest through the day.

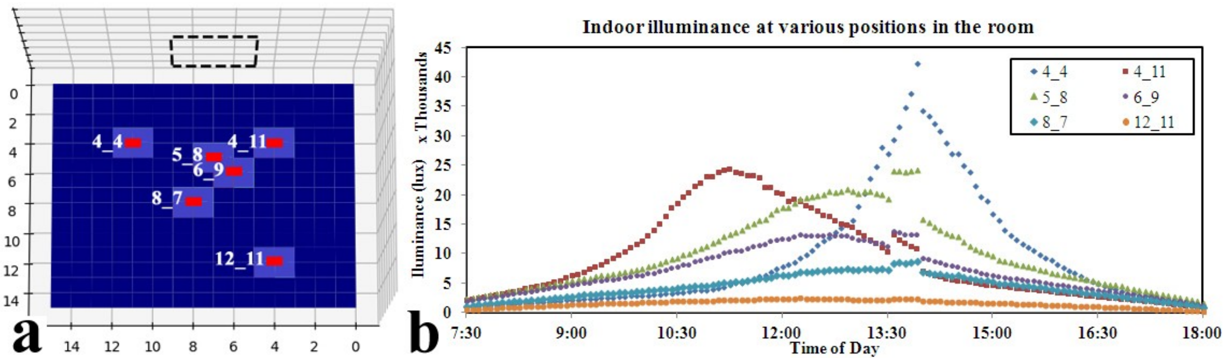

Fig. 3: (a) Representative points of interest in defined model room with south facing window, (b) Illuminance variation calculated for virtual sensors/points of interest through simulation based on measured angular sky-luminance data

4. Discussion

Space lighting complements available daylight in built environment to maintain visual comfort for the occupants. In optimized building designs, the building must have maximum useful daylight infiltration, so that minimum energy is needed for space-lighting purposes. Efficient building operations through building management systems should use controls to switch or dim electric-lights depending upon the availability of daylight at reference positions. Using our defined protocol, a building management systems may use a centralized sensor (proposed angular daylight measurement device), and calculate the available daylight at various 'virtual sensors' to control lights in real time. This has the potential of replacing multiple actual sensors over a wide district/campus — assuming similar angular sky-luminance distribution datasets over a relatively large area — thus reducing installation and maintenance costs, and simplifying operations through centralization of automated light control.

5. Conclusions

The application of a centralized sensor for real-time indoor light control has the potential of environmental integration in buildings, and this technology can complement the advances in artificial lighting technology and optical control systems.

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