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Daylight regulated by automated external Venetian blinds based on HDR sky luminance mapping in winter

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Abstract. Automated shading systems have the potential to exploit daylight in buildings to save energy of artificial lighting and cooling loads and improve occupants' visual comfort. This paper investigates the daylighting performance of automated Venetian blinds based on sky luminance monitoring and lighting computation in winter. 'In-situ' experiments were carried out in a daylighting test module when the solar elevation angle was $21.7°$ at noon. Experimental results showed the automated shading was able to maintain work-plane illuminance within [500, 2000] lux range for 88% of the working time under a clear sky and for 83% of the working time under a partly cloudy sky, while mitigating discomfort glare for occupants.

1. Introduction

Daylight is a free source of energy and has a significant potential to save artificial lighting and heating loads in buildings. Studies have also found the positive influence of daylight on occupants' well-being and productivity [1]. However, due to its variability, daylight is still regarded as an under-exploited resource in contemporary buildings. Although shading devices are commonly used in conjugation with façades to regulate the penetration of daylight, the low frequency of users' interaction with manual shading systems has contributed to the poor performance of shading devices in real applications [2].

Over the past decades, various automated shading systems have been proposed and investigated by researchers and practitioners. Early studies on shading automation were based on the incident solar radiation on windows or the illuminance on a task area monitored by a ceiling mounted photo-sensor [3] to control shading position, maintaining work-plane illuminance (WPI) within a confined range. Although a peak cooling load reduction of 28% was reported by Lee et al. [4] compared with static blinds with horizontal slats during summer in Oakland, CA, those shading systems cannot prevent discomfort glare for occupants, which was a major rejection factor of users. With the proliferation of researches on visual comfort, cameras have been investigated recently in multiple studies for shading control to monitor and mitigate discomfort glare. Goovaerts et al. [5] used a calibrated camera pointing at Venetian blinds to monitor and calculate the Daylight Glare Probability (DGP) [6] for assessing the level of discomfort glare for occupants. A closed-loop control system was employed to iteratively adjust the blind position until DGP was below the discomfort threshold. Although cameras have been used in laboratory

environment for shading control, privacy issues introduced by cameras in the building interior and field of view (FOV) of cameras occluded by occupants' movements remain impeding factors for their practical application [7]. In addition, one camera can only assess a single view direction regarding discomfort glare. For more than one occupant, numerous cameras or sensors have to be used to control a shading device by assessing different view directions, leading to to expensive, complicated and impractical installations in buildings.

In order to address the application limitations and improve occupants' visual comfort, Wu et al. [8] proposed a novel shading control system based on monitoring the sky (and landscape) luminance distribution and real-time lighting computation. With an imaging system pointing at the outdoor space, it avoids the privacy issues of indoor cameras and is able to assess multiple view directions simultaneously regarding discomfort glare for occupants, employing on-board lighting simulation. This paper investigates the daylighting performance of the automated shading system in winter when the solar elevation angle is low and occupants are vulnerable to the discomfort glare from the sun.

2. Methodology

Figure 1 illustrates the set-up of the shading controller and the installed external Venetian blinds (EVB) in a daylighting test module ($6.4 \times 2.9 \times 2.6$ m^3, facing south) in Lausanne, Switzerland ($46°31'04.0''$N, $6°33'53.6'$E). The shading controller is mainly composed of a field programmable gate-array (FPGA) processor and a calibrated imaging system [9]. Employing high dynamic range (HDR) imaging techniques, the controller is able to monitor the luminance distribution of the exterior space within seconds, including the sun, the sky, clouds, and landscape objects. The controller was positioned with its axis of the lens in the orthogonal plane of the unilateral façade to monitor the sky vault and landscape fraction facing the façade. Based on a generated high-resolution luminance map and a geometric model of the building interior, the controller is able to perform lighting simulations of work-plane illuminance (WPI) and daylight glare probability (DGP) employing the ray-tracing algorithms. It considers 15 different positions of the EVB, including fully retracted (Max) and fully stretched with slats at 72° (horizontal), 67°, 62°,..., and 7° (fully closed) to the vertical plane. The shading control is based on the simulated results of the two metrics, WPI and DGP, which are constrained in the range [500, 2000] lux and less than 0.35, respectively. The lower bound of WPI is set to maintain sufficient lighting on a task area (at 0.8 m height and 1.5 m distance to the façade) for writing and typing activities according to the European standard on lighting (EN 12464-1) [10] and the upper bound is to mitigate associated visual and thermal discomfort. The DGP calculation evaluates both view directions from the left and right and the larger DGP value of the two directions is limited within the imperceptible level of glare. Although the time consumption is between 6 and 9 min to complete one iterative on-board evaluation, including WPI calculations for 15 shading positions, generation of view images, the DGP computation, and the determination of an optimal shading position satisfying visual comfort, the controller was set to repeat the evaluation every 15 min in this paper to spare sufficient time margin. The largest opening position satisfying the constraints is determined in each iterative evaluation according to the varying sky conditions, to maintain sufficient daylight provision, mitigate discomfort glare for occupants, and secure their view outwards. Readers are suggested to refer to [8, 9] regarding details of the shading controller and employed algorithms.

Figure 1. Set-up of the shading controller and Venetian blinds

In order to assess the daylighting performance of the automated shading system, a lux-meter array was positioned inside the daylighting test module to measure the maintained WPI on the work-plane (0.8 m height and 1.5 m distance to the façade) at identical positions as those in the daylighting simulation for shading control. While the controller not only operated from morning to evening at 15-min intervals to control the EVB but also simultaneously computed the WPI for the case without shading protection as references, the lux-meter array monitored the regulated WPI by the automated shading system at a higher frequency with 30-second intervals. The experiments were carried out on Jan. 16th and Jan. 18th, 2019 for the clear and partly cloudy sky conditions respectively. During this period, the solar elevation angle was relatively low (21.7° at noon) and occupants were vulnerable to discomfort glare from the sun.

3. Results

3.1. Clear sky

The upper section of Figure 2 shows the maintained WPI achieved by the automated EVB (monitored by the lux-meter array), as denoted by green data points, in comparison with the unregulated WPI without shading protection (simulated by the controller), as denoted by the grey curve, under a clear sky on Jan. 18th. The lower section of Figure 2 presents EVB positions from morning to evening along the time line. The relatively low elevation angle of the sun increased the penetration of direct sun light, which contributed to the large values of WPI without shading protection. In the morning, the WPI was initially above 5000 lux. After the controller started to operate and determined an optimal shading position, the EVB moved from fully retracted (Max) to the fully extended position with slats inclined at 42° to the vertical plane. The WPI was dampened into the confined range [500, 2000] lux (highlighted zone in Figure 2). The EVB position almost remained at the same position throughout the day, since the sky condition changed slowly. Until 15:00 in the afternoon, when the daylight availability was insufficient, the EVB increased its opening and then retracted into the shell to allow more daylight inside. Although the WPI without shading protection surged above 10,000 lux between 10:00 and 15:00 for five hours, the automated EVB maintained the WPI within the [500, 2000] lux range for 88% of the whole working time.
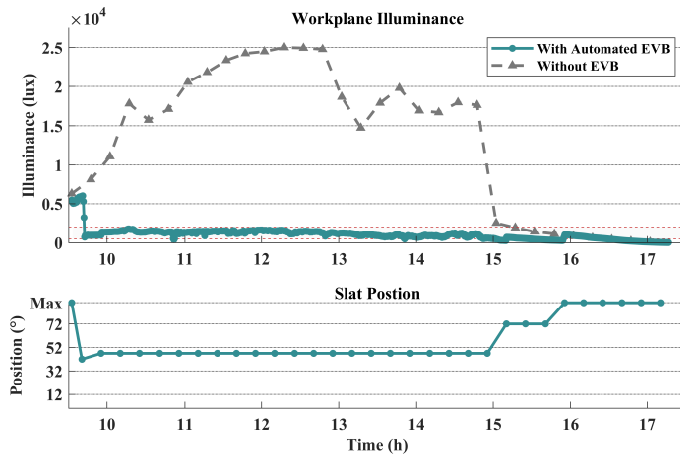
Figure 2. Work-plane illuminance (WPI) under a clear sky

Figure 3 presents the regulated DGP achieved by the automated EVB, as denoted by the green curve, as compared to the unregulated DGP without shading protection, as denoted by the grey curve, which were both calculated by the controller at 15 min intervals. At 9:30 before the controller started, the sun was in the field of view from the right view direction (south-east). Therefore, the intensive glare source (the sun) made the DGP reach 1 (the maximum value) without shading protection. After the controller evaluated the sky condition, it determined an optimal position for the EVB (fully extended and inclined at 42°), which occluded the glare source and reduced the DGP into the imperceptible level (less than 0.35, highlighted zone in Figure 3). Although the DGP without shading protection achieved the intolerable level (above 0.5) between 9:30 and 15:00, the automated EVB mitigated the DGP within the imperceptible range. Under a clear sky, less than five movements of the EVB were sufficient to satisfy occupants' visual comfort.
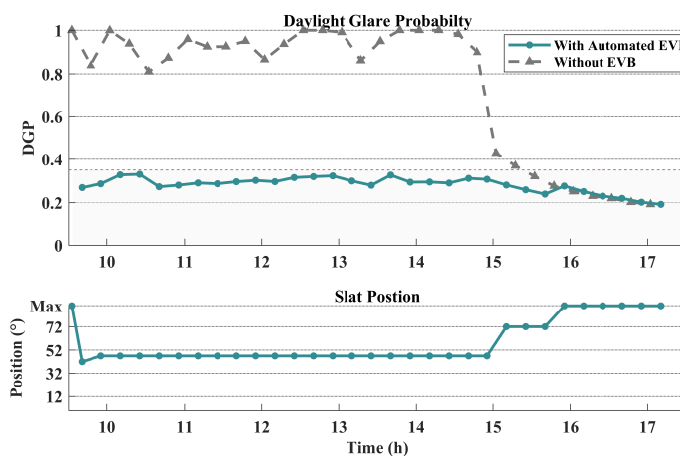

Figure 3. Daylight glare probability (DGP) under a clear sky

3.2. Partly cloudy sky

The sky condition for a partly cloudy sky is more complex than that for a clear or overcast sky, and the exterior daylight can fluctuate throughout the day frequently, since the rapid motion of clouds occlude the sun and move away within minutes or even seconds. Figure 4 and Figure 5 illustrate the WPI and DGP under a partly cloudy sky on Jan. 16th, respectively. Fluctuation

of the sky conditions is suggested by the peaky grey curves in both figures for the case without shading protection. In the morning, when the sun rose and entered the perspective of the right view direction (south-east) at 9:00, the glare became perceptible, and the controller determined an optimal position, fully extended with slats inclined at 57°, for the EVB to occlude the glare source. The EVB turned to 42° and 37° tilt angles to further occlude the sun and mitigate DGP within the imperceptible range, according to the rising solar elevation angle. When the daylight availability sharply dropped at 13:50 due to the occlusion of the sun by clouds, the EVB increased its opening to 72° to allow more daylight and secure occupants' view outside. Although exterior daylight fluctuated throughout the day, the WPI was maintained within the [500, 2000] lux range for 83% of the time, while the DGP was mitigated below 0.35. Under a partly cloudy sky, occupants' visual comfort was satisfied via more than 10 EVB adjustments by the shading controller.
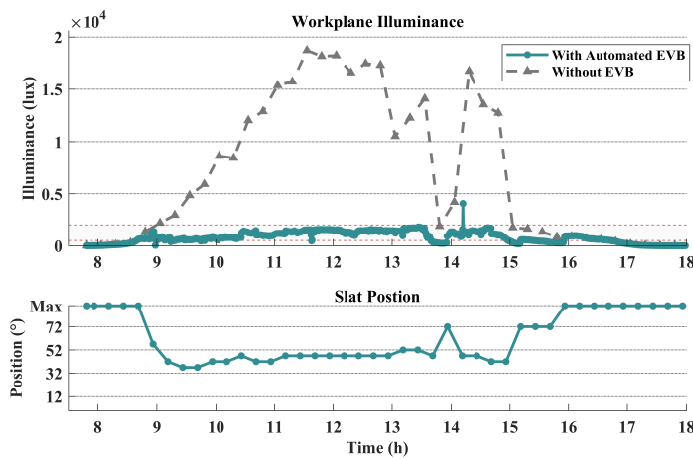

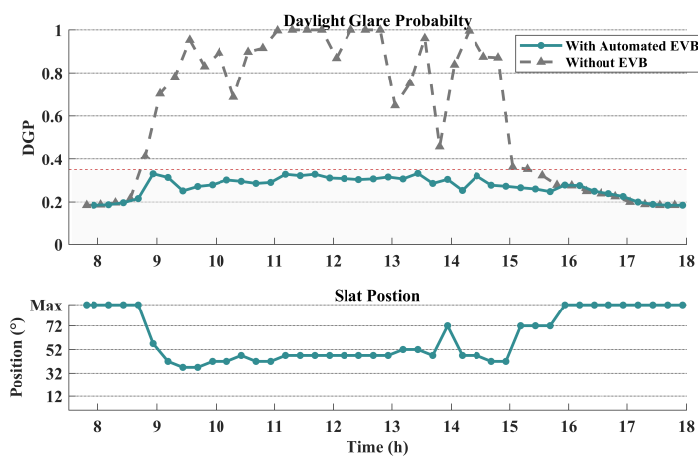**Figure 4.** Work-plane illuminance (WPI) under a partly cloudy sky

Figure 5. Daylight glare probability (DGP) under a partly cloudy sky

4. Conclusion

Well-designed shading systems have the potential to exploit daylight in buildings efficiently, which contributes to energy savings in artificial lighting, heating and cooling loads. The limited performance in glare protection and installation complexity impede conventional automated shading systems from their wide application in buildings. This paper investigates a novel automated shading system that maintains daylight provision and mitigates discomfort glare, with improved applicability.

'In-situ' experiments were carried out in a daylighting test module under a clear and partly cloudy sky in winter, when the solar elevation angle was 21.7° at noon. The results showed the automated Venetian blinds were able to maintain work-plane illuminance (WPI) within [500, 2000] lux for 88% of working time by four movements under a clear sky and for 83% of working time by 13 movements under a partly cloudy sky to cope with the fluctuations of sky conditions, while tempering discomfort glare for occupants. The majority of the movements were fine tuning of tilt angles of the shading slats, with reduced disturbance to occupants. In the future, the daylighting performance of the automated shading will be compared in parallel to a conventional automated shading system. Since the controller takes 6-9 min to determine an optimal shading position, the possibility of missing extremely rapid changes of sky conditions will be further investigated and analysed.

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