A Programmable Image Sensor for Smart Daylighting and Glare Control in Buildings

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ABSTRACT

In this study, a new programmable low-cost camera sensor equipped with a fisheye lens is used to detect the luminance and position of exterior glare sources using per-pixel analysis. The High Dynamic Range Imaging sensor is mounted on the interior surface of the window and facilitates an efficient daylight glare control framework. The control was implemented in a testbed office with automated roller shades and was compared with two commonly used solar protection control algorithms. The results showed that the new HDRI-based glare control outperforms existing algorithms and fully protects from exterior glare sources of varying luminance in real time, while maintaining visual comfort for occupants seated in daylit perimeter offices.

INTRODUCTION

Due to the significant impact of daylighting on energy consumption and occupant well-being in buildings (EIA 2012; Boyce 2014), daylighting control systems, including automated and human-oriented controllers (Shen & Tzempelikos 2012; Chan & Tzempelikos 2013; Shen et al. 2014) have been extensively studied in the last two decades. However, even the most advanced shading control algorithms fail to address glare in certain situations. A typical example is exterior reflections from adjacent building facades, pronounced in dense urban environments filled with highrise glass-curtain wall buildings. The major cause of the failure is associated with the fundamental lack of ability of the existing photosensors to identify the potential glare sources (size, intensity and location) in real-time. The limitation can be resolved by capturing and post-processing of luminance maps of the exterior scene, utilizing High Dynamic Range Imaging (HDRI) techniques. HDRI is the art of merging multiple exposure images to capture a wider dynamic range of a scene, enabling accurate measurement of the per-pixel luminance (Debevec & Malik 1997; Inanici 2006). This study proposes a novel daylight glare control framework, in which a window-mounted low-cost programmable HDRI sensor with a wide-angle fisheye lens is used to capture the full exterior luminance distribution. With proper calibration, any potential glare sources and their positions can be identified via a per-pixel analysis of the luminance map. This could prevent control strategies from underestimating the glare risk and also avoiding over-conservative shading operation. Glare detection and positioning algorithms, embedded in a proof-of-concept HDRI-based roller shade control are proposed. Finally, the proposed HDRI-based control was compared with two existing solar protection controls in a full-scale testbed office.

A PROGRAMMABLE LOW-COST HDRI SENSOR

The HDRI sensor used in the study is constituted of an 8 mega-pixel camera board and a single-board computer (Figure

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1). As the objectives of the study required to maximize the sensor's field-of-view, a custom 180-degree wide-angle fisheye lens was attached to the sensor. The single-board computer runs on a Linux operating system and can run open-source Python-based scripts that have been created to cover every part of the method presented in this study. To attach the sensor to the interior window glazing, a custom-designed camera mount was 3D printed as shown in Figure 1b.

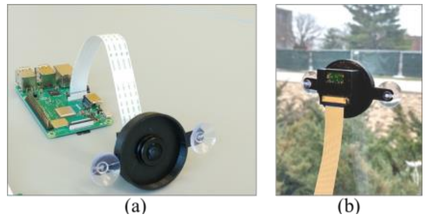

Figure 1 (a) Camera module integrated with a single-board computer (b) Window-mounted camera sensor.

To accurately measure the scene luminance, photometric calibration was performed following the process introduced by Inanici (2006). Geometric calibration was also performed to estimate camera parameters essential for positioning of glare sources from the HDRI sensor-captured scenes. Scaramuzza's omnidirectional camera model validated up to 150 degrees FOV was used as the fisheye model (Scaramuzza et al. 2006). The calibration was validated by comparing the vertical illuminance computed from the luminance maps and the calibrated photosensor readings following the same procedure as in Konstantzos et al. (2015).

REAL-TIME GLARE SOURCE DETECTION AND POSITIONING USING THE HDRI SENSOR

The overview of glare source (including the solar disk) detection & positioning is illustrated in Figure 2. From the HDR luminance maps created by merging multiple low-dynamic images, potential glare sources are instantaneously identified. Since there is no global consensus for glare detection threshold in this case, an absolute luminance threshold of 30,000 cd/m^2 (19.3 cd/in^2) was used in this study, based on previous research (Jakubiec and Reinhart, 2012). Note that the red-colored pixels in the image represent the solar disk, which is detected when luminance exceeds 380,0000 cd/m^2 (245.2 cd/in^2 ,near the maximum measurable value by the HDRI sensor). To effectively calculate the identify and group glare source pixels, an open glare analysis tool, Evalglare (Wienold et al. 2002) was used. As shown in Figure 2b, Evalglare identifies bright sources above the threshold and then groups the neighboring pixels into a single glare source, displayed by the same colors. In addition, we modified the original C++ script to retrieve the boundary information of the detected glare sources and output the bounding box pixels of each glare source (Figure 2c).

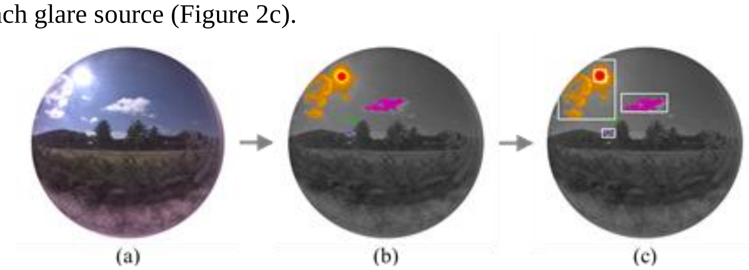

Figure 2 Overview of glare source detection & positioning. (a) HDR luminance map (b) Glare source detection via Evalglare (c) Glare source bounding box retrieval. Red color-mapped pixels represent solar disk detected.

The exact positioning of the detected glared sources is identified by back-projecting glare source pixels (solving a trigonometric function based on geometric parameters estimated) in terms of the profile angle. The lowest profile angle across all detected glare sources can be retrieved by calculating profile angles corresponding to all bottom corner pixels of the sources and finding the lowest among them. This method simplifies the profile angle calculation from highly distorted fisheye luminance maps while guaranteeing that the calculated value is equal to the actual lowest profile angle of all sources.

EXPERIMENTAL STUDY

A roller shade control algorithm, designed to protect occupant's eyes from glare sources above 30,000 cd/m^2 (19.3 cd/in^2), was implemented in a testbed office and compared with two existing shading control algorithms. The proposed control is based on a cut-off strategy that moves the shade to a position that completely blocks the detected exterior glare source from the eyes of the occupant seated at a certain distance away from the window, in real-time. It assumes that the relative profile angle observed from the window-mounted sensor and the occupant are the same, which is a valid for typical urban environments (distance greater than 10 m (32.8 ft) between two adjacent buildings). The two existing shade control logics were: i) a typical "solar-tracking" control, which always moves shades to block direct sunlight from the occupant's eyes; ii) a "rule-based" control that moves the shade to the occupant's eye height whenever transmitted illuminance exceeds a threshold (8,000 lux or 743 fc) that is bound to cause glare, and fully opens the shade otherwise. The performance of the three shade control logics was compared under rreal sky conditions while also using an artificial reflector (additional glare source) placed outside the building, 15 m (49.2 ft) away from the façade during clear, sunny days (Figure 3a). The rotatable reflector was able to create a wide range of luminance, up to 332,000 cd/m^2. For each reflector position, the three control logics were operated in a sequence within a minute time window. Meanwhile, an additional interior HDRI sensor was placed at the occupant position - 1.5 m (4.9 ft) away from and facing the window - to collect luminance maps created by the different control logics, as perceived by the occupant.

Figure 3 presents sample luminance map results captured from window and occupant positions with different shade controls in a one-minute time frame. Both existing shading controls fail to protect the occupant from the bright reflector in real-time, while the HDRI-based control moves the roller shade to the position that just blocks the reflector.

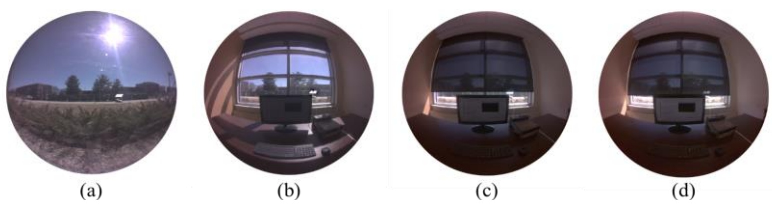

Figure 3 (a) Exterior luminance map captured by window-mounted HDRI sensor and white reflector installed outside as an additional glare source (b – d) Luminance maps captured from occupant position with different shade control logics - b: "Solar-tracking" control; c: "Rule-based" control; and d: Proposed HDRI-based control.

CONCLUSION

A new daylighting glare control framework based on a window-mounted, low-cost programmable HDRI sensor was developed and implemented in this study. With proper calibration, the sensor can be used to identify and locate potential glare source pixels. More specifically, the sensor made it possible to identify small but extremely bright sources – via Evalglare analysis - which can hardly be achieved with the conventional photosensors used in existing daylighting controls. A roller shade control logic based on HDRI glare source detection was implemented and compared with two common glare control algorithms in a testbed office. The HDRI-based glare control outperformed existing algorithms, exhibiting itself as the only control logic that provided full protection from all exterior glare sources of varying luminance in real time.

ACKNOWLEDGMENTS

This work was supported by Lutron Electronics Co Inc. and the Center for High Performance Buildings at Purdue University.

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