VALIDATION AND PRELIMINARY EXPERIMENTS OF EMBEDDED DISCOMFORT GLARE ASSESSMENT THROUGH A NOVEL HDR VISION SENSOR

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ABSTRACT

In spite of an abundant research on visual comfort models and integrated day- and electric lighting systems, the lighting engineering and research community is restricted to the use of ceiling-mounted luminance sensors, which do not faithfully reproduce the visual comfort sensations of building users in day-to-day practice. Moreover, the discomfort glare indices suggested in the past are evaluated through the luminance mapping of visual scenes generated by the way of a laborious High Dynamic Range (HDR) imaging process: this approach cannot be integrated into building automation. On the other hand, mitigation of the electricity demand for lighting by applying ‘easy’ photometric metrics, such as the luminance monitored from the ceiling, leads mostly to non-optimal situations regarding visual comfort and performance. In order to overcome these issues, a novel embedded HDR vision sensor fitted with a fisheye lens and capable of performing real-time, accurate and reliable luminance mapping together with an assessment of discomfort glare indices, is suggested. This novel device was successfully validated against the Evalglare software and its robustness on an embedded platform for long-term visual comfort assessments was demonstrated. Preliminary experiments were carried-out with two calibrated HDR vision sensors in order to deepen our knowledge regarding visual comfort in an office room of the LESO solar experimental building located on the EPFL campus in Lausanne (Switzerland). These experimental results are beneficial for the design phase of a sun shading and electric lighting control system that will be shortly evaluated on-site within the same occupied office room.

Keywords: Integrated day and electric lighting, high dynamic range vision sensor, discomfort glare indices, Evalglare software, embedded glare assessment, sensitivity analysis.

INTRODUCTION

In modern societies, around 90% of people spend most of their time in buildings. Indoor comfort, such as thermal and visual comfort, plays accordingly a significant role and has a large impact on the inhabitants’ health, morale, working efficiency and satisfaction. Moreover, buildings account for more than one-third of total primary energy demand in the Western World and for more than 30% of the CO_2emissions [1]. Thus, there is an urgent demand for introducing practical solutions for mitigating the energy demand while maintaining the users’ comfort in the built environment.

Visual comfort and lighting energy demand are fields that are not addressed properly by practitioners in spite of profound progress made by research during the past 30 years. Several metrics for quantifying the discomfort glare sensation, such as the Daylight Glare Index (DGI), the CIE Glare Index (CGI) and the Daylight Glare Probability (DGP), were developed through extensive field monitoring. However, despite of that, ‘easy to use’ variables, such the vertical and/or horizontal workplane illuminances remain the principal criteria for assessing the performance of daylighting and electric lighting systems. One of the impeding factors for implementation of the very valuable theoretical developments is the absence of an accurate and reliable monitoring device capable of performing luminance mappings of visual scenes, similar to the human eye. Traditionally, this process is achieved by merging several Low Dynamic Range images captured with different exposure intervals in an attempt to reach a High Dynamic Range (HDR) imaging, capable to handle the sunlight with a deep and dark shadow in the same picture.

Recently, a few field studies were performed to address this issue by means of the traditional approach. Bellia et al. [2] used a classic HDR camera only for evaluation of glare indices (e.g. DGI). In 2010, Van Den Wymelenberg et al. [3] carried out a controlled study involving 18 participants in a daylit single-occupancy office to examine the applicability of 150 visual discomfort predictors. The study showed that the most effective predictor was the average luminance of the glare sources. In 2014 Konis [4] conducted a study in the core zone of a side-lit office building located in San Francisco, California. Subjective measurements of visual comfort were collected using a repeated-monitoring study involving fourteen participants over two weeks under clear sky conditions. The results showed that the discomfort indicators based on luminance contrasts and window luminance were more effective than glare metrics or more basic measurements such as the vertical or horizontal illuminance.

This paper presents the methodology used for the implementation, integration and validation of a novel HDR vision sensor for monitoring of visual comfort indices within office rooms.

METHODOLOGY

The specifications of the vision sensor are presented herein. On the other hand the robustness of the performance and the measurements capability of the device are explained. The validation procedure of the data monitoring by means of the renowned software *Evalglare* [5] is elaborated. Once the reliability of the measurements by the vision sensor was established, a sensitivity analysis of the photometric metrics with respect to its position and orientation was carried-out. In the next step, the main photometric variables were measured from different viewpoints using both HDR vision sensors. This 'on-site' monitoring allows a comparison of visual comfort assessments carriedout for an optimal location of the HDR vision sensor (user's point of view when sitting at his/her desk) with a more convenient one from a practical perspective (HDR sensor mounted on the VDT screen).

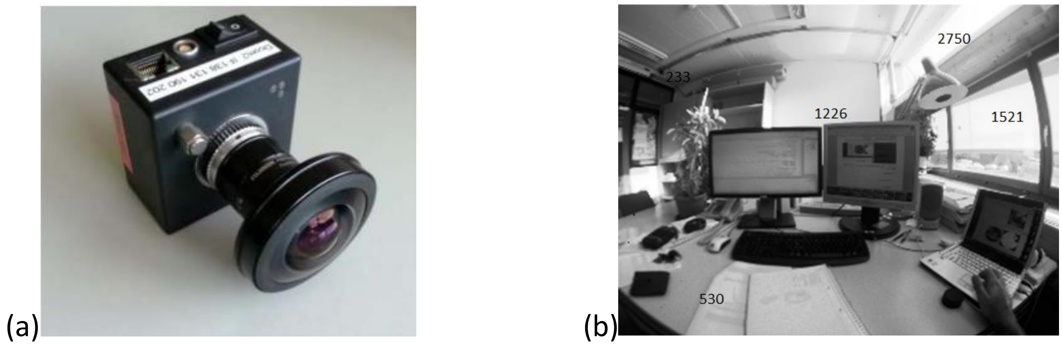


Figure 1: (a) *IcyCAM HDR vision sensor equipped with fisheye lens;* (b) *the captured luminance map*

HDR VISION SENSOR

Thanks to a fruitful collaboration between EPFL/LESO-PB and the Centre Suisse d'Electronique et de Microtechnique (CSEM), a novel embedded HDRI sensor (Figure 1 (a)) was developed and calibrated [6]; the photometric device allows real-time capturing and analysing of luminance maps of visual scenes with considerable accuracy and speed. It offers a 132dB intra-scene dynamic range encoded logarithmically with 149 steps per decade. Each HDR image therefore provides a complete record of the magnitude and spatial variation of the luminance in the field-of-view. Besides, its powerful system-on-chip (SoC) platform (32-bit DSP processor, 500MHz [7]) allows performing concurrent image processing for calculating discomfort glare indices. Finally, this “artificial retina” was photometrically, spectrally and geometrically calibrated and equipped with fish-eye lens.

EMBEDDED DISCOMFORT GLARE ASSESSMENT

To date, the Evalglare software, a Radiance based tool for glare risks evaluation developed by Wienold [8], constitutes a reference for glare indices assessments. An embedded programme inspired by Evalglare was developed in order to perform a glare indices calculation on the HDR vision sensor. The essential features of the embedded program are: i) its computational efficiency (each cycle takes ~12 second); ii) an accurate image processing in spite of limited embedded RAM memory and iii) a telemetry transmission feature of whole records of a visual comfort analysis over LAN to a remote machine (MATLAB based interface).

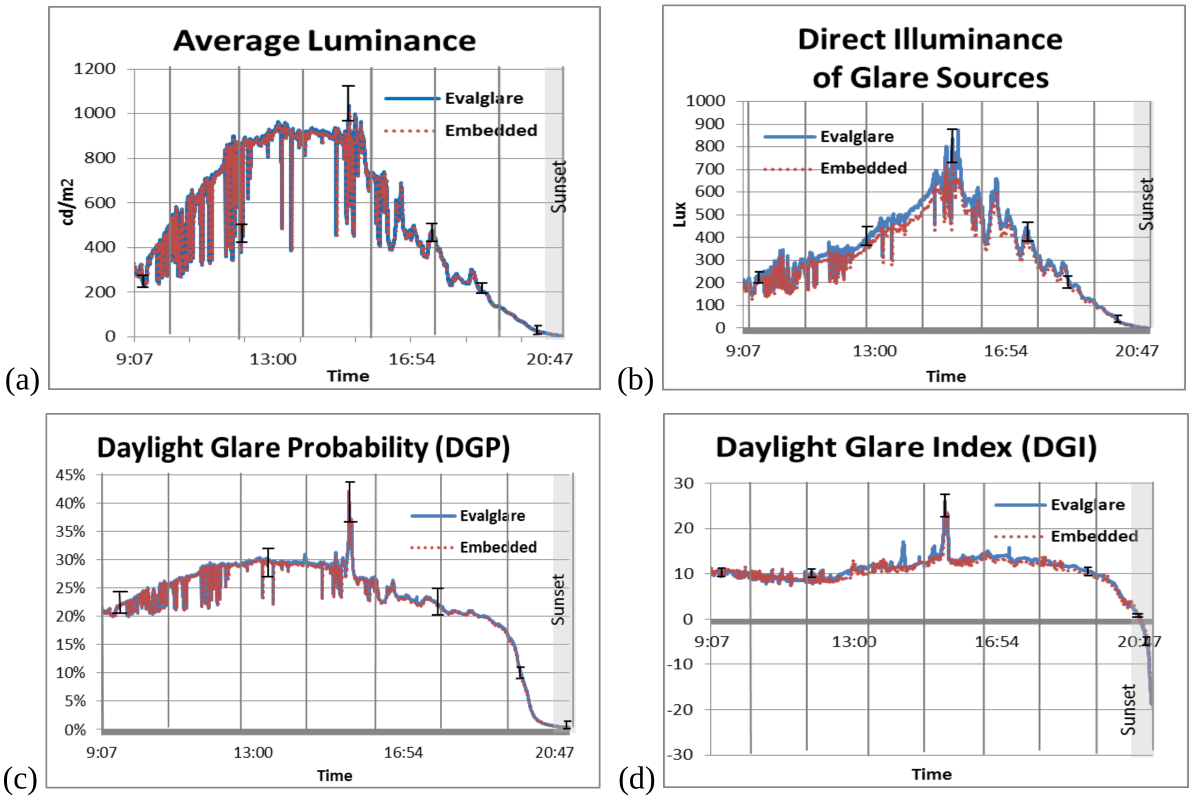
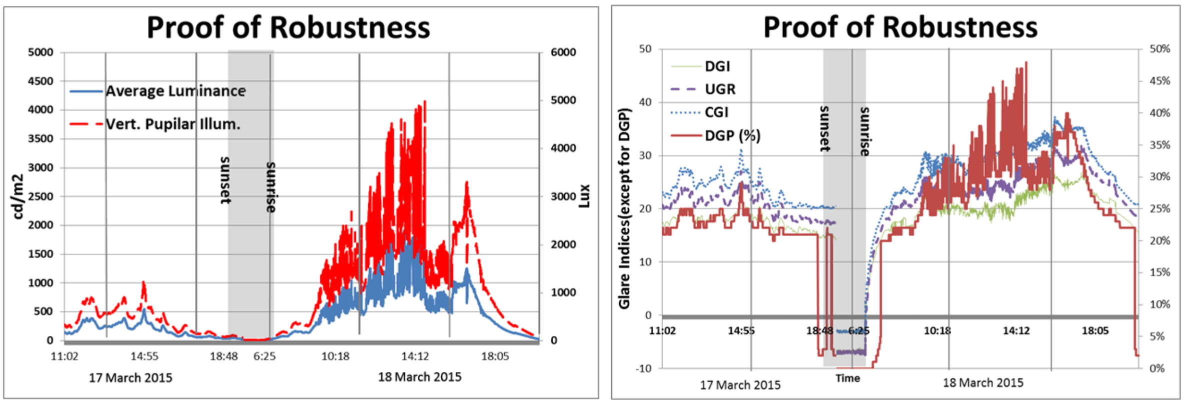


Figure 2: Validation of the HDR vision sensor embedded glare indices calculation versus the Evaglare software [5].

The software was validated through comparison of 5400 measurements captured under clear sky during approximately 18 hours from 9:20AM to 6:10AM on March 16 & 17, 2015; the sensor location is illustrated in Figure 5(b) (reference sensor). As shown in *Figure 2*, a reasonable matching was observed between the photometric variables (average luminance and direct illuminance of the glare sources) and glare indices (DGP and DGI) monitored with the sensor and those calculated with Evalglare. The relative discrepancy for the average luminance, the direct illuminance of glare sources, the DGP and DGI shows RMS values of 0.9%, 8.9%, 2.5%, 6.7% respectively. According to [9], the accuracy (average error) of the HDR vision sensor for daylight conditions with respect to a luminance meter (Minolta LS 110) was estimated around 20%.

PROOF OF ROBUSTNESS

In order to verify the robustness of the functioning of the HDR vision sensor, it was positioned in the location indicated in Figure 4(b) for more than 33 hours; the sun shadings were completely open and the office occupied for regular office tasks during that period. The electric lighting was turned on from 6:45 PM to 8:55 PM on the first day. The day was partially cloudy and the second day sunny. During the latter, the sun disk was visible by the sensor: very large vertical pupilar illuminances for some moments of the day were accordingly observed. These illuminance values were properly reflected in the DGP (and to some extend in the CGI) while the other indices return values comparable to those monitored for overcast sky conditions. This observation is due to the strong linear relation of the DGP with the vertical pupilar illuminance.

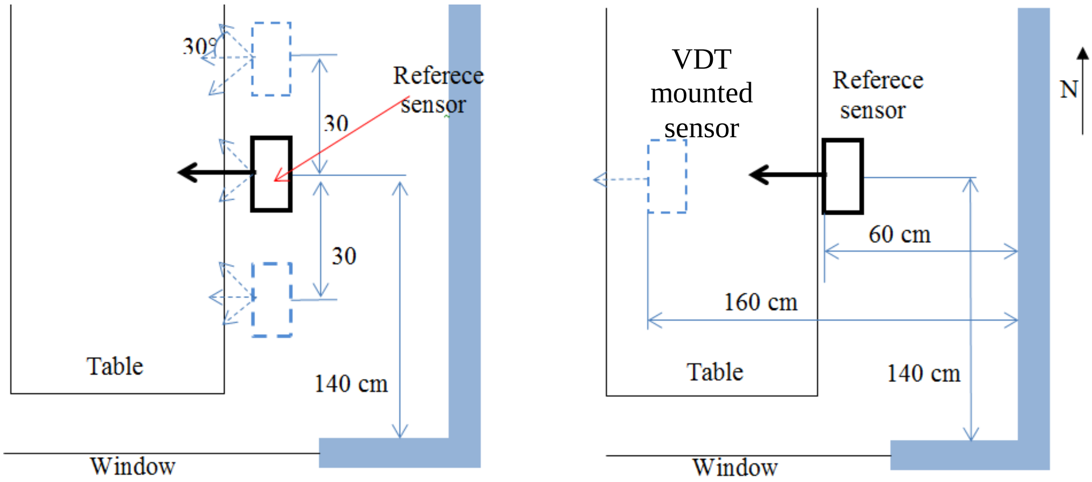


(a) (b)

Figure 3: Proof of functionality robustness of the HDR vision sensor during approx. 33 hours; (a) principal photometric variables: vertical pupilar illuminance (lx) and average luminance (cd/m2); (b) glare indices DGI, UGR, CGI and DGP

PRELIMINARY OBSERVATION

The purpose of these preliminary 'on-site' experiments was to assess the discomfort glare sensations of an office worker by the way of the HDR vision sensor mounted on his/her VDT screen. This study provides with a sound monitoring of the person's visual comfort in order to set up a fuzzy logic controller managing both the daylight and electric light fluxes in an office room. The experiments were carried out in a south-facing office room located in the LESO experimental building on the EPFL campus in Lausanne, Switzerland. Two calibrated HDR vision sensors were used for that purpose, the corresponding 'on-site' monitored photometric variables being coherent in terms of accuracy and reliability with well-known glare calculation software.



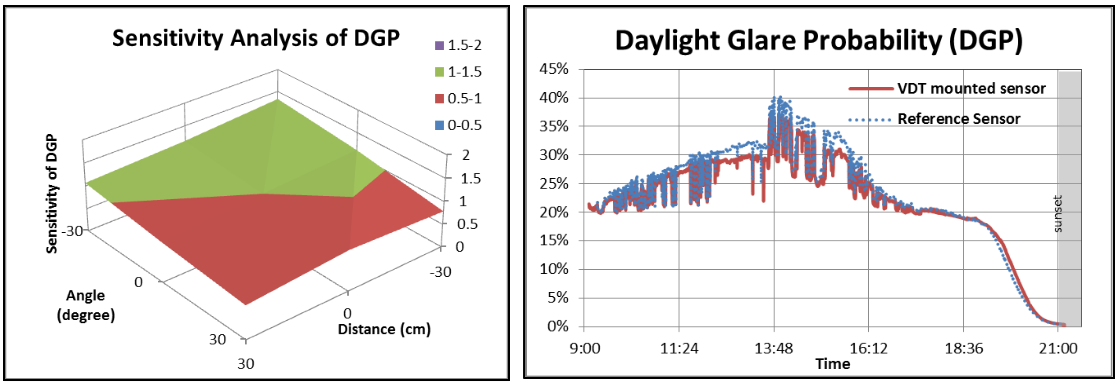
(a) (b)

Figure 4: Top view of the preliminary experimental setups; a) Sensitivity analysis; b) Comparison of visual comfort assessments from two different viewpoints. The solid box and array represent the reference HDR vision sensor.

A sensitivity analysis as well as a comparison of the visual comfort perceived at the desk by the office worker and the one monitored on the VDT screen (Figure 4), were carried out. The 'on-site' monitoring was carried out first by placing the HDR vision sensor in a way that it points toward the default user Field of View (FoV) and by applying translational and angular variations to the second device. Each experiment was performed for at least 15 minutes, including 60 snapshots. The second experimental setup was organised as shown in Figure 4(b) and performed for 12 hours (9:00AM till 9:00PM, 3040 measurements) under a clear sky.

RESULTS

The results show that DGP is less sensitive to a position variation than the average luminance and the vertical pupilar illuminance. On the other hand, the DGP is less sensitive to translational variations with respect to a rotational one. Moreover, the relative variations of the DGP reach a maximal value of *32%* in comparison the reference value. Thus, the DGP of experienced value for a typical user sitting at his desk moving ±30*cm* and ±30° from a reference position/orientation may vary of about ±*32%* around the DGP measured from the reference position/orientation.



(a) (b)

Figure 5: (a) Sensitivity analysis of DGP with respect to translational and angular displacement; (b) Comparison of DGP measured from two points of view according to the experimental setup of Figure 4(b).

The comparison of the DGP measured from the reference viewpoint (eyes height of an office worker) and the one measured from the VDT screen (dotted line on Figure 5,b) shows that the evaluated glare indices follow a very similar trend; those measured at the VDT screen remains lower to the reference values. The RMS of the relative discrepancy between the two DGP readings sets is close to 11%; the latter is equal to 3.2% for the discrepancy of the absolute DGP values).

DISCUSSION AND CONCLUSION

It goes without saying that the closer the sensor is to the lateral window, higher the recorded photometric variables are. The DGP formula follows a linear function (with $R^2 = 0.98$); it is expected accordingly that the observer experiences visual discomfort sensations in the range of 30% around the values measured from reference point. On the other hand, the sensor placed on the VDT screen sensed in an acceptable way the same photometric variables measured from reference viewpoint (observer eyes). The difference between these two readings is moreover lower if glaring sources are absent of the observer FoV (before 11:00AM and after 4:00PM) as shown on Figure 5(b)).

A novel HDR vision sensor was set into practice for an "on-the-fly" discomfort glare assessment within an office room. A glare index calculation algorithm was set up and embedded on the device for this purpose. The sensor is able to achieve visual comfort monitoring accurate enough to be compared to Evalglare software calculations on a PC. The device is accordingly ready for integration in a smart building control system for the optimisation of visual comfort in an office room and minimizing the lighting energy demand.

ACKNOWLEDGMENTS

The authors would like to thank Ms. Sigolène Bechetoille Pangaud (CSEM) for her important contribution to this work. This work was fully supported by Swiss Competence Centre for Energy Research (SCCER), in the framework of the Future Energy Efficient Building & Districts (FEED&B) project.

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