Building and Environment 125 (2017) 26–38

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Shading control strategy to avoid visual discomfort by using a low-cost camera: A field study of two cases

C. Goovaerts [a, *], F. Descamps [a, c], V.A. Jacobs [b]

[a] Vrije Universiteit Brussel (VUB), Architectural Engineering Lab (ae-lab), Pleinlaan 2, 1050 Brussels, Belgium
[b] Vrije Universiteit Brussel (VUB), Light and Lighting Research (LUXETEC), Pleinlaan 2, 1050 Brussels, Belgium
[c] Daidalos Peutz, Vital Decosterstraat 67A, 3000 Leuven, Belgium

ARTICLE INFO

Article history:
Received 26 May 2017
Received in revised form
13 August 2017
Accepted 16 August 2017
Available online 18 August 2017

Keywords:
Visual discomfort
Manual override
Control strategy
Low-resolution camera
High dynamic range
Daylight glare probability

ABSTRACT

Daylighting in offices creates a comfortable and healthy working environment for its users. However, maximizing the amount of daylight can cause visual hindrance. To improve the visual and thermal comfort for the users, designers implement shading systems, which control the transmitted solar and visual radiation. To ensure a comfortable indoor environment, designers need to choose an appropriate control strategy. Different control strategies exist, but the acceptance and satisfaction of the user regarding these strategies remains quite low. Therefore, we developed a control strategy that is based on the comfort requirements of the users. The control strategy aims at avoiding visual discomfort for the user, while optimizing for daylight availability and improving user satisfaction by providing the possibility to override the automated control of the shading system. This is the first study where a shading device is controlled by a controller system with a low-resolution camera. The controller system captures High Dynamic Range images and evaluates a visual comfort parameter, namely the 'Daylight Glare Probability'. The system controls the actuator of the shading device based on the assessed level of comfort. This paper demonstrates two experimental case studies where the controller system and the control strategy are implemented. The controller system is able to keep the visual hindrance below a predefined limit, while sufficient daylight can still enter the office room.

1. Introduction

Daylighting in offices creates a comfortable and healthy working environment for its users [1]. Additionally, daylighting has a positive impact on the global energy savings, because it decreases the energy consumption for artificial lighting [2]. Next to providing daylight, another important aspect for the user satisfaction is providing a view to the outside [3,4]. However, maximizing the amount of daylight may cause some issues. In particular, visual hindrance is the most negative side effect from windows. Also, excessive shortwave directly-transmitted solar radiation and longwave indirectly-transmitted energy can result in thermal discomfort and an increased energy demand for cooling. Thus, it is important to control the transmitted solar radiation to improve the visual and thermal comfort for the users. In Northern European climates, designers find it useful to implement shading systems, which can adapt themselves to changing weather conditions. Commonly used adaptable systems are adjustable in either horizontal or vertical direction (e.g. roller blinds, movable panels or venetian blinds). However, the overall performance to improve visual and thermal comfort, depends on their control strategy.

Different shading control strategies exist to achieve a comfortable indoor climate. A widely accepted control strategy for venetian blinds is tilting the slats to their time-dependent cut-off angle. As a result, the slats block the direct incident solar radiation and they allow diffuse light to enter the office space [5–7]. In this case, an outside view for the user is largely preserved. Other control algorithms use control parameters to adjust the shading system. As an example, Thalfeldt and Kurnitski [8] simulate different control algorithms based on their impact on the energy performance and duration of unobstructed view. They propose to use the horizontal illuminance on the working plane as a control parameter during working hours and the temperature of the room as a control parameter for shading control outside working hours. Another study, of Gunay and O'Brien [9], uses the ceiling illuminance as a control parameter to open the indoor roller blinds and to turn off

* Corresponding author.
E-mail address: charlotte.goovaerts@vub.ac.be (C. Goovaerts).

http://dx.doi.org/10.1016/j.buildenv.2017.08.030
0360-1323/

the artificial lighting when sufficient task lighting is provided. This strategy reduces the electricity demand for artificial lighting up to 25%. Although the aforementioned strategies control the transmission of solar radiation, researchers evaluate their performance merely by checking the impact on the energy need, without considering the visual comfort of the user. Karlsen, Heiselberg and Bryn [10] use questionnaires to explore the user satisfaction. The users indicate the preserved outside view as an advantage of the cut-off angle strategy, but as a disadvantage, users indicate that using the cut-off angles is not always sufficient to avoid glare. The cut-off angle strategy can cause glare by a specular reflection of light on the slats of the venetian blind.

The choice of an appropriate control strategy, which avoids visual discomfort, is crucial for user acceptance and satisfaction. Furthermore, users prefer a user-controllable indoor climate and, in general, they do not accept a fully automated control strategy. The choice of manually controlled shading strategies improves the user's visual comfort and satisfaction. However, the fully manual controlled shading systems are more often closed than required. This results in lowered thermal and visual comfort and in an increased energy demand for artificial lighting [11,12]. To overcome the issues in fully automated or fully manual controlled shading strategies, designers can give the user the possibility to override the automated control. Different studies, using different control parameters and strategies exist.

In this section, some examples and recommendations are given on these manual override actions and the resulting user satisfaction. Next, some examples are given which can improve the user acceptance by using an adaptive user-learning control strategy and by providing feedback. A field study of Meerbeek et al. [13] investigates how office workers react to an automated control of venetian blinds with the possibility for manual override and the option to turn off the automated control. The results show that a large majority of the users choose to turn off the automated mode. The study concludes that the perceived level of control influences the visual comfort assessment of the users. A study of Reinhart and Voss [14] shows that using only vertical illuminance as a control parameter for an automated venetian blind control strategy leads to low user acceptance. As in this case, 88% of the automated control actions are overridden by users. Bakker et al. [15] also investigate in a field study the influence of an automated control strategy on the user satisfaction. This study uses varying control strategies where the position of the roller blinds is pre-determined or controlled by vertical illuminance. Each of the scenarios is tested with and without a manual override option. The results reveal that a manual override of the automated roller blinds leads to a higher user satisfaction regarding the illuminance levels in the interior environment and the view out. In addition to these results, an implementation of an adaptive-learning strategy can improve the user satisfaction even more. The results of Gunay and O'Brien [16] show a decrease of 80% in the override actions by the users when using an adaptive user-learning control strategy. Their study demonstrates in a numerical simulation context the preferences of a user regarding manual control, automated control with fixed set-point for illuminance and adaptive user-learning control of the venetian blinds. Furthermore, another study shows that making the user aware why a certain control is implemented also increases the user satisfaction. Namely, Meerbeek et al. [17] use a gradual light feedback system to communicate the intentions of the automated venetian blinds to the users. This reduced the amount of override actions by the user from 50,8% to only 3,6%.

It is clear that the possibility of a manual override of an automated control strategy leads to higher user acceptance and satisfaction, but the chosen control strategy and control parameter influence the amount of override actions. A promising and robust parameter for evaluating visual comfort related to daylight [18,19] is the 'Daylight Glare Probability' (DGP) parameter. This parameter has a good correlation to what a person actually perceives [20]. Other glare parameters are mostly suitable for artificial lighting or indirect sunlight [21].

Hence, we need an appropriate control strategy that avoids visual discomfort, while minimizing the number of override actions by the user through an adaptive user-learning algorithm, and while optimizing the daylight availability on a working plane to ensure a comfortable and healthy working environment. Instead of using multiple sensors for daylighting, and shading control and sensing the presence of a user, there is a potential to use a camera as a replacement of these multiple sensors [22]. Therefore, we developed a control strategy, based on the 'Daylight Glare Probability' as a visual comfort parameter. We used a small, low-cost, and multifunctional single-board computer, namely a Raspberry Pi, with an attached low-resolution camera as a controller system. This controller system is developed by the authors at the architectural engineering research lab of the VUB, during the European project Smartblind (PF7 314454) [23]. First, the controller system evaluates the visual comfort in the interior environment, by taking pictures and evaluating them. Second, based on the results of the assessment, the controller algorithm decides whether the position of the shading system should be changed or not. Each time-step the controller system sends a control signal to the actuator of the shading device [24]. A user can override the automated control and at this point the controller algorithm adapts itself to the preference of the user. The adaptive response of the controller system helps to anticipate and minimize the number of override actions.

The goal of this research is to develop an improved control strategy which can optimize visual comfort and at the same time reduce the energy consumption for heating, cooling and the electricity use for artificial lighting. By using the DGP as a control parameter of a shading device, we can improve the visual comfort for the user and by allowing a manual override, we increase the user acceptance and satisfaction. This paper demonstrates the performance of the control strategy and validates the low-cost controller system through in-situ measurements in two case studies. The first case study consists of a mock-up office cell with a venetian blind as a shading device. The tests were performed with and without the presence of a user. The second case study consists of a real office environment, namely an open-plan office space with 56 users and adaptable external roller blinds.

2. Procedure and measurements

2.1. Glare metrics

The DGP parameter is used to assess the visual comfort. The software tools Radiance [25] and Evalglare [26] are used to evaluate glare for each luminance map. An illuminance sensor measures the vertical illuminance at the position of the camera and this value is inserted into Evalglare, to ensure an accurate calculation of the DGP. Glare sources are identified as the areas where the luminance exceeds 5 times the average luminance in the image. The value of 5 is defined as the optimal setting [21]. The DGP value depends on the view direction and the position of the viewer in the room and is calculated by (1)

$$DGP = 5.87\cdot 10^{-5}\cdot E_v + 9.18\cdot 10^{-2}\cdot \log\left(1+\sum_i \frac{L_{s,i}^2\cdot \omega_{s,i}}{E_v^{1.87}\cdot P_i^2}\right) + 0.16 \quad (1)$$

where E_v [lux] is the vertical illuminance, L_s [cd/m^2] is the