Energy and Buildings 149 (2017) 58–72

Contents lists available at ScienceDirect

Energy and Buildings

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

On-site monitoring and subjective comfort assessment of a sun shadings and electric lighting controller based on novel High Dynamic Range vision sensors

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ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form 22 April 2017
Accepted 6 May 2017
Available online 15 May 2017

Keywords:
Building automation
Energy-efficiency
Fuzzy logic controller
HDR vision sensor
Office lighting
On-site monitoring
Visual comfort and performance

ABSTRACT

Electric lighting is responsible of about one fifth of the electricity demand of buildings in Switzerland. Therein, integrated control of sun shadings and artificial lighting can mitigate the electricity demand while maintaining the user comfort and performance. However, the drawback of the existing smart building technologies is that they do not take visual comfort effectively into account, one of the essential aspects of indoor human comfort. An 'on-the-fly' measurement of a visual comfort index, Daylight Glare Probability (DGP), by a novel High Dynamic Range (HDR) vision sensor was introduced into the building control system optimizing the sun shadings position and electric lighting status. Two identical office rooms (*reference* and *advance*) of the LESO solar experimental building were occupied by 30 human subjects during 15 afternoons and were used to experimentally compare the performance and users acceptance of the fuzzy logic based control system against a best practice reference system. A paper-based and a computer-based visual tests, subjective self-reported visual comfort surveys and precise monitoring of the electric lighting consumptions were carried out.

The results indicates that the electricity demand of the *advanced* system is 32% lower than the *reference* one. It also shows that, while the subjects' visual performance remain comparable in the two office rooms, the *advanced* control system is successful in preventing discomfort glare sensations.

1. Introduction

The Swiss Federal Council announced in 2011 its decision to withdraw from nuclear energy on a step-by-step basis. Thereafter, the Swiss parliament has adopted the resolution to mandate the Swiss Federal Office of Energy (SFOE) to elaborate for the country the new Energy Strategy 2050. The strategy urges for energy efficiency in different domains of activities in Switzerland, including the buildings sector.

Buildings account for more than one-third of total primary energy demand in the Western World; they are also responsible for more than 30% of the CO_2 emissions [1,2]. Electric lighting can represent up to one third of the electricity needs in office buildings [3,4]. According to Franzetti et al. [5], 'it is generally assumed that about 30% of the energy consumption of office buildings comes from artificial lighting'. Although these figures cannot be extrapolated to the whole building sector, they indicate that the building research community agrees that addressing artificial lighting loads in buildings is noticeably important and that energy-efficient lighting solutions need to be promoted [6].

However, energy-efficiency and electricity demand are not the only items to consider when it comes to designing appropriate lighting solutions for buildings: visual comfort and performance are of course equally important. In order to provide with an appropriate visual performance for paper reading/writing in office rooms, the horizontal illuminances (especially on the workplane should be 300 lx or 500 lx depending task and activity) must be sufficiently large and distributed in a homogenous way on the work-plane (appropriate illuminance uniformity, i.e. $U_o \geq 0.4$); discomfort glare sensations e.g. from luminaires and/or through windows must also be avoided (Unified Glare Rating (UGR) <19 for office environment) [7]. Obviously it is not an easy task to reach the two objectives, lighting energy-efficiency and proper visual comfort of users all together. A significant reduction of the lighting demand will in most cases result in lower work plane illuminances and might therefore have a negative influence on the occupants visual performance. There are, however, other studies [8] showing that illuminance on the work plane before turning on the electric light is less than 500 lx at 98% of the time and less than 147 lx in 50% of the time. In

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http://dx.doi.org/10.1016/j.enbuild.2017.05.017
0378-7788/

another study, prior research on visual comfort in office buildings equipped with Anidolic Daylighting System (ADS) has shown that under certain circumstances much lower illuminance levels seem to be sufficient [9]. Keeping the work plane illuminance constantly at a large level would boost the electricity consumption of office rooms.

Several studies have demonstrated, however, that building occupants are usually poor in making a rational usage of the daylighting by controlling the shadings and blinds at their disposal [10], for instance, monitored three office rooms in central London whose occupants were found to leave on average 40% of the buildings glazed area occluded by their venetian blinds, without any obvious correlation with the available sunlight. Nonetheless, the building occupants will very likely reject automating shading devices and electric lighting, if visual comfort and performance is not maintained in the working space and if amendments of shading positions and/or lighting levels are too numerous. Moreover, Paul et al. [8] showed that the manually controller sun shadings are very few and poorly used; less than 2 movements blinds/week regardless of the orientation or season. The consequence of this misuse is that the contribution of natural light is far from being optimized.

One of the earliest Daylight-Linked Control (DLC) systems was proposed by Rubinstein et al. [11]. They elaborated three different control algorithms for maintaining constant total light level on a desk surface through photo-electrical lighting system. Ever since, a great number of control systems are proposed by researchers and practitioners. Despite benefits, their use is limited. Bellia et al. [12] recently presented an interesting review underlying the main obstacles to DLC application in three categories: (i) lack of knowledge about specific sensors such as photosensors and their calibration, (ii) lack of calculation tools to justify the interventions from economic point of view and finally (iii) peoples interpretation on *control* systems that might limit their freedom in their environment. Extensive research is carried out in recent years to address these three issues. Firstly, Doulos et al. [13] in 2014 proposed a multi-criteria decision making tool to facilitate the commissioning procedure of ceiling-mounted photosensors and estimate their best position and field of view. The proposed methodology is verified through simulations as well as experimental setup. Moreover, the same researchers in 2008 has targeted second obstacle by quantifying the energy saving potential of DLC systems and consequently estimating the payback period. 18 commercial electronic dimming ballast (EDB) are tested and their transfer functions of light output versus power input were extracted. These pieces of critical information were applied in a series of simulations for close loop and integral reset scenarios. Finally, Sadeghi et al. [14] performed extensive experiments to extend the current knowledge of human-building interactions to advanced shading and lighting systems. They monitored physical variables, actuation and operation state of building systems as well as non-physical variables such as occupant comfort and perception. Xiong et al. [15], through simulated and experimental setup, successfully demonstrated the application of model based control (MPC) algorithms which utilizes a fast reliable semi-analytical lighting-glare model to compute the interior lighting conditions, lighting energy use and Daylight Glare Probability, for predetermined shade positions, based on the readings of the sensors on each building facade. Their approach aimed at minimizing lighting energy use while satisfying glare constraints which resulted in reduced shading operation.

The best practice for daylight-linked electric lighting and shading control within non-residential buildings, if existing at all, relies on the measurements of ceiling mounted rudimentary luminance meters. This approach guarantees neither that the users visual comfort and performance nor an optimal energy management of the electric lighting and shading is achieved. A device based on a novel High Dynamic Range (HDR) vision sensor providing with an accurate luminance mapping in a room was considered in this study. The main goal of this study, thus, is to investigate the electric lighting energy saving potential by appropriate application of a novel HDR vision sensor in the building automation system (BAS). The inclusion of this sensor in an advanced electric lighting and shadings controller would solve the aforementioned issues by mitigating the lighting energy demand and enhancing the visual comfort and performance of the occupants.

Traditional HDR imaging techniques [16,17] were used pervasively as an *assessment tool* in lighting design and engineering, but not as a *vision sensing technology* for control purposes. In 2014, Konis [18] published the result of his study conducted 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 over two weeks under clear sky conditions involving fourteen participants. Subjective data was paired with concurrent luminance measurements acquired using a conventional HDR imaging technique resulting in a total of 523 observations. The study showed that the discomfort glare indicators based on luminance contrast ratios and absolute luminances in a lighting scene were more effective than glare indexes or basic lighting metrics such as vertical/horizontal illuminance. In another study, Fan et al. [19] installed a classical HDR camera on several workstations in order to set-up a methodology facilitating the long-term monitoring of visual comfort in a real working environment. This method was later applied during a field-based study in an academic building comprising a five-perimeter zone for workstations [20,21]. Having collected nearly 4800 subjective glare assessments paired with HDR images over a year, the authors observed that several basic variables derived from HDR images, such as the vertical illuminance measured at the eyes level (pupilar illuminance), show a stronger correlation with the subjective glare assessment than the current glare prediction models, such as the Daylight Glare Index or the Unified Glare Rating.

Hirning et al. [22] used an approach where data was collected at workstations in five buildings in Brisbane Australia. Office workers filled out a subjective survey while an HDR image of their primary task view was acquired using the classical HDR imaging technique. This nomadic approach enabled the researchers to collect 493 surveys paired with HDR images acquired from office workers; however each workstation was surveyed once at seemingly arbitrary moments during varying seasonal conditions. Data were collected sporadically over 14 days from February to October 2012, covering the spring, autumn and winter periods. The benefit of this approach resulted in a subjective feedback from a larger number of study participants. However, as daylit spaces are highly dynamic, and vary in response to daily and seasonal changes according to the sky conditions, the approach presents a number of limitations for relating subjective outcomes with monitored data. As an example, luminance measurements were acquired during overcast sky conditions or a daily period when sunrays are not impinging on the facade adjacent to the workstation; however the participants subjective response may still rate the space as glary due to a recent past experience of an expected glare sensation occurring later in the day.

The HDR vision sensing technology described in this paper allowed for the first time to set-up an on-the-fly discomfort glare rating sensor which can be used as input variable for an electric lighting and sun shading control system.

A detailed description of this novel equipment as well as the experimental setup used for a first lighting control application is given in Section 2. The control platform, as well as the corresponding control approach, is presented in Section 3. The experimental design and procedure, in addition to the methods used to obtain the subjects assessments of the office room lighting conditions are given in Section 4. The results are respectively presented and dis-