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Experimental study on modelling and control of lighting components in a test-cell building

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ABSTRACT

The perfect control of shading devices, particularly venetian blinds can significantly improve the rational use of daylight in buildings and provide enhanced visual comfort for occupants while saving the electricity that would be used for artificial lighting. This study proposes a control strategy for building lighting components including daylighting and artificial lighting to automatically adjust the amount of light level (or the illuminance) in an office building as required and block direct sunlight from entering the office when necessary. The proposed control strategy is based on a hybrid statecharts model mainly consisting of a supervisor control system that chooses appropriate control actions for a current sky condition depending on the sky ratio and clearness index. These control actions are implemented to automatically adjust the blind height and slat angle, and turn on the artificial lighting only when needed. Real experiments on the test-cell case study demonstrating the effectiveness and flexibility of the proposed control strategy are presented and discussed at the end of this paper.

1. Introduction

Nowadays, buildings are the largest consumers of energy in the developed world. In Europe, for example, the 2016 updated (or revised) European Union (EU) Directive on the Energy Performance of Buildings (EPBD) has set out measures for member states to reduce energy consumption by at least 20% by 2020, and to achieve much greater efficiency improvements by 2030, because buildings (residential and tertiary) are responsible for more than 40% of energy consumption and 36% of CO_2 emissions in the EU (European Commission, 2016). According to EU Commission data, electrical appliances and lighting constitute about 11% of total energy consumption in the residential buildings. In contrast with the tertiary buildings, space heating constitutes about 52% of total energy consumption while lighting and the operation of office equipment constitutes about 14% and 16%, respectively. The directive urges EU countries to help promote the use of smart technology in buildings so that from 2020 all new buildings must be nearly Zero-Energy Buildings (nZEBs). In proportion to these energy trends (i.e. savings), many research studies including e.g. (Hinkle and Schiller, 2009; Kolokotsa et al., 2010) stated that energy use in buildings can be reduced by 50% or more, without compromising comfort, by applying proven and innovative technologies. Therefore, the integration of advanced control systems in buildings or buildings environments is required to minimise operation costs and especially energy consumption while maintaining or even improving occupants' comfort and well-being.

It is argued that because they are speedy, accurate and reliable and also have been applied successfully to a variety of large-scale complex systems and mainly in the domain of space and aeronautics (e.g. Tomlin et al., 1998) and automobiles (e.g. Lygeros et al., 1998), advanced control techniques are then very important for comfort and energy management in building environments. Therefore, the development of advanced control systems for building performance applications such as heating, humidifying, air conditioning, ventilation and daylighting can be effective means of achieving energy efficient and high-performance buildings.

In view of daylighting application, although it provides a major opportunity for energy savings, it also confronts several technical problems, including glare and heat. Several studies have been conducted on the development of intelligent control systems for sun-shading devices including venetian blinds, awnings, and shutters. These include self-adjusting control systems for indoor environments based on integration of thermal comfort and visual comfort (Dounis et al., 1993), self-adaptive adjusting parameters for daylighting and solar control of buildings (Guillemin and Morel, 2001), combining control systems for shading devices and electrical light savings (Athienitis and Tzempelikos, 2002), and indoor lighting controls based on fuzzy logic controls (Lah et al., 2005). In Koster (2004) estimated that the application of advanced control systems for building lighting components can decrease energy costs for buildings by 30–50% in most situations by providing adequate quantity and quality of daylight in interior spaces.

There have been a number of research studies, in which different

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control algorithms and strategies were developed and applied to building daylighting and electric artificial lighting. For example, Koo et al. (2010) presented a work on a control method for automated venetian blinds to maximise occupant comfort and benefits of daylight in buildings, Zhang and Birru (2012) a work on an open-loop control of blind height and slat angle based on an analytic model of solar position, and geometrical blind and window parameters to avoid direct sunlight and to enhance daylight utilization in buildings, and Chan and Tzempelikos (2013) a work on the development of venetian blind control strategies based on some pre-defined illuminance and light distributions while considering daylight provision, lighting energy use and visual comfort in buildings. However, there is still a room of improvement for better control of daylighting and glare provided through windows equipped with motorised venetian blinds and of rational artificial lighting use in buildings. Most studies were principally devoted to theoretical considerations, and less to the modelling of dynamics for the purposes of control applications in real buildings. For this reason, this paper presents an efficient control strategy based on a hybrid statecharts model that mainly consists of a supervisor control system that chooses appropriate control actions for a current sky condition depending on the sky ratio and clearness index. These control actions are implemented to automatically regulate the blind height and slat angle, and turn on the artificial lighting only when it is required to meet the illuminance setpoint. A test-cell building case study which is equipped with motorised venetian builds is used here to demonstrate the effectiveness and flexibility of the proposed control strategy.

Further experiments showed that the heating energy consumption is low when the position of the blinds is open due to the insulation of the sun during the winter (Bauer et al., 1996). However, practically all of these studies have some limits as the control laws developed to automatically adjust the position of the blinds and the angle of the blind slats are not coordinated and not precise. In addition, fuzzy logic control is popularly used for controlling such complex systems without taking into account their dynamics and the sun's apparent movement over the course of day and year. Moreover, the obtained results are rather ambivalent; the methods introduced to control the shading devices, especially the motorised (or automated) venetian blinds, cannot be applied more generally.

Therefore, an improved method to design control systems for motorised venetian blinds was proposed to automatically adjust both the position of the blinds and the angle of the blades in the test-cell on the basis of the required indoor illumination levels and the sun's apparent movement and position throughout the day and seasons. These motorised venetian blinds are controlled in order to provide the room with daylight and to shade its space from sunlight (from glare or direct sun) while maintaining the indoor daylight to the required illumination level and the glare to an acceptable level. Moreover, the control actions of both the position of the blinds and the angle of the blades are coordinated in order to avoid overheating and overcooling of the room while achieving occupants' visual well being and increasing building energy efficiency.

This study concerns an experimental study on control and monitoring of lighting components in a test-cell building. Performing experiments requires using a computer to receive input data, perform operations, and send the output results. The design of an advanced control system often requires a mathematical model of the controlled plant or process in the form of a transfer function or state-space representation. The control accuracy and reliability of an advanced control system strongly depends on the accuracy and reliability of the model. For this reason, this study covers the mathematical analysis and modelling of lighting components within a building.

2. Objective

The main objective of this study was to design a control system that created a comfortable indoor lighting climate in an office building while taking full advantage of daylighting (i.e. sunlight) and minimising energy consumption. Visual comfort is the main determinant of lighting requirements: sufficient levels of light for occupant activities and tasks ensure and enhance visibility and visual performance in building spaces. Other factors such as age and gender are also important for the satisfaction of indoor visual comfort, but they are not considered in the study.

Several different control system designs were tested in order to take maximum advantage of (a) natural resources while maintaining the indoor climate of an office building at desired, comfortable working conditions and (b) weather conditions by using passive devices during the occupied and unoccupied period.

2.1. Case study

A test-cell at the Delft University of Technology, the Netherlands (52°N, 4.1°E), designed as an office building, was employed to investigate the integration of advanced control systems in building performance applications, especially in real time, in order to provide occupants with consistent thermal, visual, and indoor air quality comfort while minimising energy consumption and taking full advantage of natural resources including wind and sun. However, here, the objective is only to accomplish a comfortable indoor lighting environment at the lowest energy consumption possible. The test-cell was of thermally light construction, had a double skin facade (DSF) oriented about 30° east of south in order to capture as much the sunlight as possible for lighting of its space, as shown in Fig. 1a and b, because this was positioned in relation to the course of the sun during the day. The internal size of the test-cell was $3.1\,\mathrm{m} \times 1.9\,\mathrm{m} \times 2.68\,\mathrm{m}$, with a window surface of $3.1\,\mathrm{m} \times 1.9\,\mathrm{m}$ and was placed at 0.8 m above the floor. Next to the test-cell was the monitoring room, as shown in Fig. 1d.

Next to the first skin facade was the cavity where the shading device (venetian blinds) are placed. The shades served as blinds when the device was unrolled vertically along the first skin facade and as blades (i.e. blind slats) when the shading device rotates horizontally to face the first skin facade. Dampers (or valves) were placed at the bottom of the cavity to control the airflow through the cavity. Next to the cavity was the second skin facade, which is composed of three transparent glazing panels of the facade. Fig. 2 illustrates the section view of the test-cell, its monitoring room, and the devices that were remotely monitored and controlled from the monitoring room.

The test-cell was equipped with several actuators, i.e. motorised windows, dampers, venetian blinds, artificial lighting, mechanical ventilation (fan for exhaust or air supply), electrical heater, humidifier and air-conditioner. *Matlab/Simulink* was installed on the computer in the monitoring room to control different devices (actuators) placed in the test-cell. The control systems regulating the devices in the test-cell were developed and called by the *TestPoint* program, which was developed to also record and display all data from all sensors. Fig. 3 shows the *TestPoint* interface, which illustrates the disposition of all sensors in the test-cell.

For the control of illuminance distribution, the test-cell was also equipped with several sensors for light-intensity (*ls*) and solar radiation (*lsK*) placed outside and inside the room on a vertical position, and on a horizontal position to/from the wall of the window facade. The weather station was placed on the roof of the test-cell, and the indoor lighting sensors were placed vertically about 1 m from the window façade of the test-cell.

2.2. Components of the test-cell

2.2.1. Double skin facade

DSF consists of the outer (or second skin) facade, the cavity, and the inner (or first skin) facade. The second skin facade is generally used to provide protection against the weather and external noises. It also contains openings at the bottom and top of the facade for ventilation of