MODEL-BASED SHADING AND LIGHTING CONTROLS CONSIDERING VISUAL COMFORT AND ENERGY USE

Jie Xiong[1], Ying-Chieh Chan[1], Athanasios Tzempelikos[1]

1: School of Civil Engineering, Purdue University, 550 Stadium Mall Dr., West Lafayette, IN 47907 USA

ABSTRACT

Dynamic facades with high performance glazing and automated shading have the potential to balance daylighting, comfort and energy use, when integrated with lighting and thermal control systems. This paper presents the development and implementation of a model-based control algorithm for automated shading and lighting operation, aiming at minimizing energy use while reducing the risk of glare. A detailed validated lighting-glare model is used to compute real-time interior lighting conditions, lighting energy use and DGP, based on the readings of two sensors on every building facade. The model-based operation ensures optimal shade position and light dimming levels that minimize energy use while satisfying glare constraints at each time step. The developed algorithm is demonstrated in a full-scale office space, controlling shades and electric lighting in real-time, using simple sensor readings as inputs. Finally, a comparison between control strategies and control intervals is discussed.

Keywords: Model-based control, facades, shading, glare, daylighting

1 INTRODUCTION

Façade design and control, integrated with lighting and thermal controls, should provide natural light while minimizing energy use and maintaining human comfort. To evaluate the impact of advanced control strategies, accurate and efficient models of dynamic façade and lighting systems are needed [1], and proper comfort indices. Fisher et al. [2] utilized an accurate illumination model for electric lighting control, trained by measurement from light sensors located at every seat. Shen et al. [3] studied independent and integrated open and closed loop strategies for shading and lighting. Kim and Park [4] used EnergyPlus as a model-based predictor for optimal slat angles within a 24 hr time horizon, with high computational effort. Thorough work on blind controllers with multi-objective optimization processes [5-6] provide promising solutions. Very few studies directly associated glare indices with shading controls. Wienold [7] used the simplified DGP to evaluate the efficiency of shading controls towards glare. Yun et al. [8] used DGP to evaluate blind control strategies towards glare and energy and stated that E_v is a good criterion for shading control. However, it is implied that no direct light conditions were met. Obtaining real-time DGP data is quite challenging. As the DGPs approximation uses only vertical illuminance, the potential of a model-based control based on DGPs needs to be investigated [9].

Real-time detailed simulation requires extensive sensor networks for acquiring necessary information with changing weather and sky conditions. In addition, improper or separate controls for façade and lighting systems could be ineffective and costly. Therefore a low-cost but reliable model with less exogenous inputs should be established. In this way, model-based control algorithms could be effective in management of façade, interior lighting and comfort [10]. This paper presents the development and implementation of shading and lighting model-based control algorithms based on different criteria, for the case of spaces with interior roller shades. The control was able to minimize lighting energy use while maintaining good visual comfort. Advanced control options that consider variable control intervals are also discussed.

2 METHODOLOGY

2.1 Model-Based control logic

Fig. 1 presents the flowchart of the developed model-based control (MBC) methodology. Input data (measured by sensors for real-time control or TMY3 for an annual analysis) are used together with space geometry to calculate interior illuminance and luminance distributions based on a validated hybrid ray-tracing and radiosity daylight model [11]. The model combines the accuracy of forward ray tracing for direct light with computational efficiency of radiosity for diffuse light entering the space. In the case or roller shades, the angular direct-direct and direct-diffuse transmittance is calculated using a validated semi-empirical model [12]. Other models can be used for different types of complex fenestration systems. The model outputs include work plane illuminance, vertical (on eye) illuminance, and DGP for a pre-selected calculation grid (occupant positions and view directions). These are calculated at each time step for 11 pre-defined shading positions (every 10%), from fully open to fully closed shades. Having discrete positions significantly improves computational efficiency. The sets of simulation results are then sent to a control decision maker. The decision maker selects the "highest" shading position (among the 11) that satisfies the following criteria, to maximize daylight provision and reduce lighting energy use at each time step. Three control criteria are compared in this study as shown in Fig. 1:

1. DGP-based control. The highest shading position for which DGP≤0.35 is selected. Daylight Glare Probability is calculated based on the original equation [13].
2. Vertical illuminance-based control. Recent studies [9] showed that DGPs, the simplified version of DGP, which depends only on vertical illuminance on the eye (E_v), is appropriate to use for all cases except when direct light falls on the eye.

$$DGPs = 6.22 \times 10^{-5} E_v + 0.184 \quad (1)$$

   DGPs equal to 0.35 corresponds to E_v= 2670 lx. Adding a small safety factor, the highest shading position for which $E_v \leq 2500$ lux is selected. Note that shades with noticeable openness transmit direct light–for these cases, the use of DGPs is not recommended [9].
3. Effective illuminance-based control. The highest shading position for which work plane illuminance $E_{wp} \leq 2000$ lx is selected, without any direct sunlight reaching the work plane. Instead of real-time simulation for this control, a threshold of effective transmitted illuminance through the window and the shade, E_{eff}, can be selected, corresponding to E_{wp}=2000 lx for the position closest to the windows (including the presence of shading). The advantage is that only one sensor on the window is required. The threshold is based on pre-calculated simulated results and will vary with orientation, and room geometry.

   If all shading positions fail to pass the comfort criteria, the shades would be left closed. After that, the controller extracts the simulated work plane illuminance (on the calculation grid) corresponding to the selected shading position and dims electric lights based on a work plane illuminance set point (500 lx). Light dimming can be implemented locally (per fixture or row of fixtures) or, for smaller rooms, based on the averaged E_{wp}. Lighting energy use is calculated from corresponding light dimming levels.

3 CONTROL IMPLEMENTATION IN A FULL-SCALE OFFICE

3.1 Experimental facility

Two identical, side-by-side test offices (Fig. 2), part of the Architectural Engineering Laboratories at Purdue University were used to implement the developed model-based control strategies. The offices (5m x 5.2m by 3.4m high) are equipped with reconfigurable façade, shading and lighting systems for investigating the impact of façade design and control options on indoor environmental conditions and energy use. The south facing façade has 60% WWR. Both rooms are equipped with a high performance glazing unit (normal visible transmittance = 65%), and motorized roller shades (beam-total transmittance = 5%, measured with an integrated sphere). In each room, there are four light fixtures (two rows parallel to windows) with 54-W, T5 HO lamps. LICOR calibrated photometers were used to measure light levels, both exterior (horizontal and vertical illuminance) and interior (transmitted through window, horizontal work plane illuminance at several points, and vertical illuminance at the eye height level at 2.20 m from the window). Direct and diffuse incident solar radiation on the façade was measured with a SPN1 solar pyranometer, mounted on the exterior south wall. Some of these measurements are used as inputs in the model-based control. A calibrated Canon 550D dSLR camera, equipped with a Sigma 4.5mm fisheye lens was used for luminance mapping and glare measurements, located at a distance of 2.20m from the glass and in the center of the room. The calibration data was implemented in Labsoft v14.3.6, which was used for HDR creation, image processing and DGP calculation following the logic of Evalglare [14]. The control platform is a combination of Matlab and LabVIEW. Data acquisition and control output are handled by LabVIEW, while and model runs in Matlab using a built-in MathScript function in LabVIEW. Control commands for shades and lights are sent to respective devices using Ethernet connections.

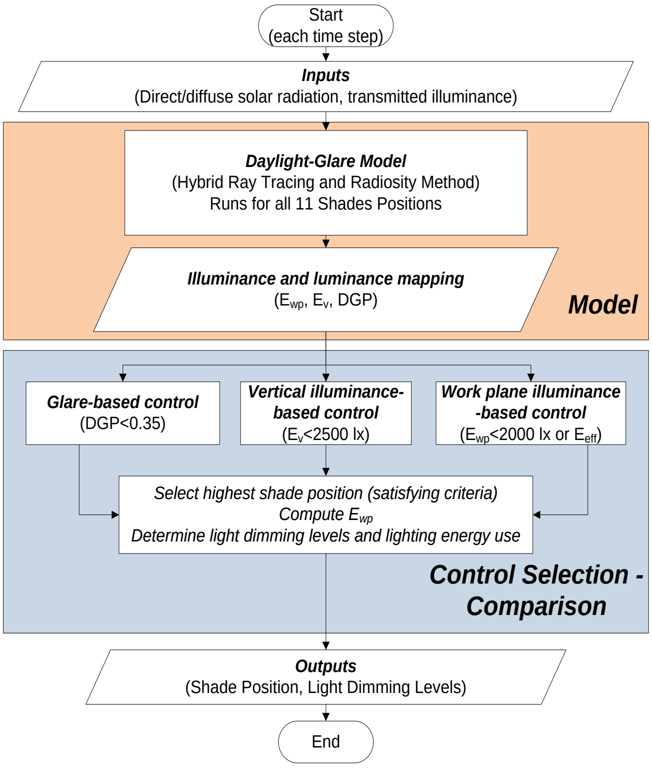

Figure 1. Model-based Control Flowchart

Figure 2. Exterior and interior views of the test offices and HDR camera

3.2 Implementation of model-based control strategies

The three control strategies were tested in the offices during February-April 2015, under a variety of sky conditions. Real-time measurements were used as inputs to the model, which runs every minute. A 5x5 work plane calculation grid was used. The threshold of E_{eff} for these offices is 6000 lux (work plane starts at 0.5m from the window). Electric lights were dimmed as a group, using 500 lx as a set point for averaged work plane illuminance. This was achieved by mapping dimming levels and E_{wp}, which will differ depending on the space and lighting system configuration and lighting control scheme. Representative results for three successive days –one cloudy, one mixed and one sunny- are shown in Fig. 3. The control system responds fast to changing outside conditions. Overall, the three control strategies were successfully implemented, achieving their objectives, while sufficient daylight is provided and electric light levels remain very low. The DGP and E_v-based controls result in similar illuminance and DGP conditions –measured DGP levels are maintained below 0.35 while E_{wp} remains high. The E_v-based control seems to be a stricter criterion than DGP, since resulting work plane illuminances (Fig. 3f) are lower. The E_{eff} control results lower shading fractions, higher DGP values (up to 0.4) and higher E_v values (up to 3500 lx), therefore it might result in instances with glare. However, the resulting E_{wp} values are higher with the DGP-based control.

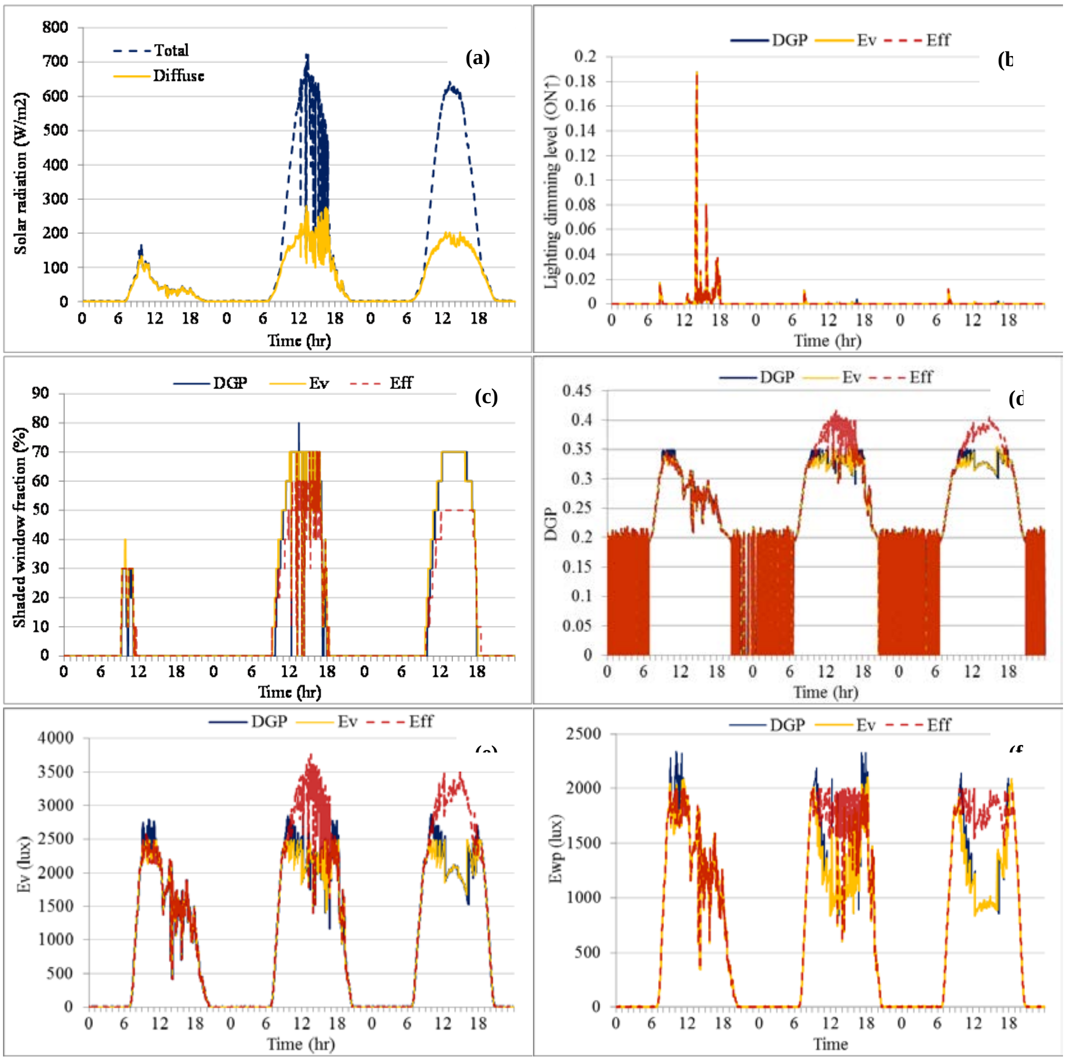

Figure 3. Experimental results using the three MBC strategies: (a) incident solar radiation on the façade (b) measured light dimming levels (c) recorded shading positions (d) camera-measured DGP (e) measured E_v and (f) measured E_{wp}.

3.3 Development of variable control interval strategies

To prevent frequent shading and electric lighting operation this, a different logic was developed (Fig. 4) using longer and variable control intervals, protecting from glare during mixed sky conditions (passing clouds), while otherwise reducing shading movement. Measurements are still recorded every minute but control actions are separately decided. In each time step, the shade position (MSP) predicted by the model-based control is compared with the current shade position (CSP). If MSP < CSP, which means shades need to lower for glare protection, control action is taken within a minute to move the shades to CSP, and the timer is reset to 0. If MSP > CSP and shades have not moved during the last 15 min, shades are set to the lowest MSP position recorded in the past interval; otherwise they remain in their current position and the timer moves to the next step. The new logic was implemented in the offices, to evaluate its effectiveness and compare with the 1-min control operation. Results for a day with turbulent sky conditions are shown in Fig. 5 for the DGP-based control option. The shades move less frequently while visual comfort is well maintained (DGP<0.35) even under fast-changing conditions. Lighting energy use is slightly affected, while E_{wp} is reduced.

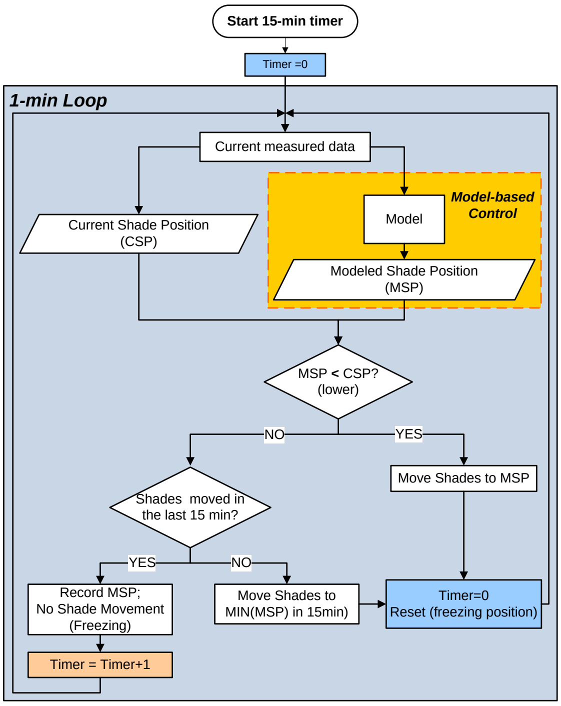

Figure 4. Variable Shading Control Interval Logic

4 CONCLUSION

This study presents advanced model-based shading and lighting control algorithms, aiming at minimizing lighting energy use while maintaining visual comfort using a small number of sensors. Three control criteria, based on DGP, vertical and horizontal illuminance were compared. The control strategies were successfully implemented in test offices with satisfactory results. DGP values remain below 0.35 for most cases while work plane illuminance levels were adequate. Lighting energy use was significantly reduced with all controls. The model-based control is able to capture rapidly changing sky conditions and take appropriate action. An advanced control interval logic was also successfully implemented, resulting in less frequent shade movement. The developed model and controls can decrease sensor network complexity while retaining reliability. Future work includes applying the developed controls in occupied offices, to evaluate human satisfaction and interactions; as well as thermal environment considerations for delivering integrated control solutions.

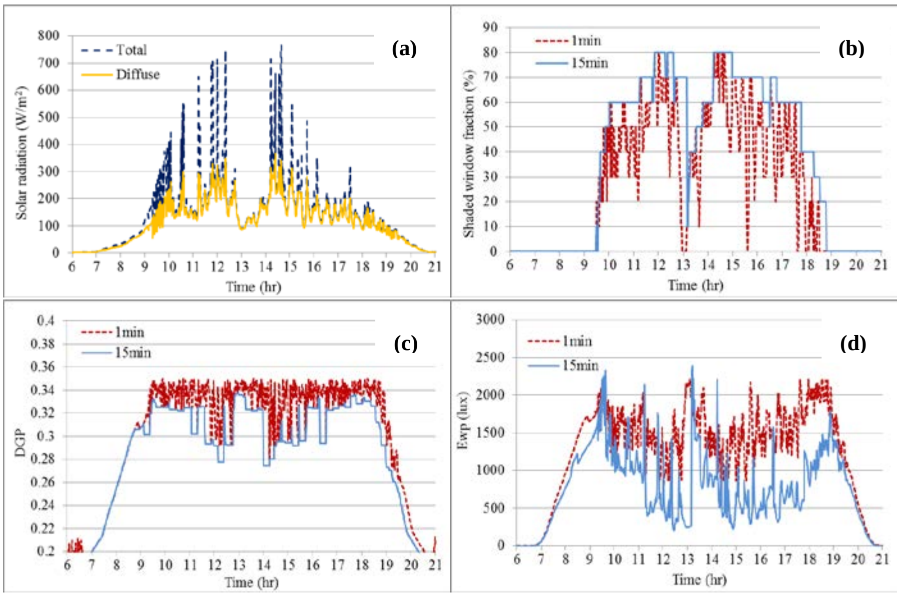

Figure 5. DGP-based results with 1-min vs variable control interval: (a) incident solar radiation (b) recorded shading position (c) camera-measured DGP (d) measured E_{wp}.

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