A Review of Automated Control Strategies of Blinds Considering Glare Prevention and Energy Saving

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Abstract In recent years, a large number of studies have shown that shading devices have great potential in saving energy, improving indoor thermal comfort as well as preventing glare. As a passive strategy, the shading devices have great value to improve building performance sustainably. Appropriately, the shading control strategies can effectively utilize daylight in interior space that benefit an occupant's health, well-being, and productivity by preventing glare and overheating while indoor lighting, cooling and heating loads are reduced. The venetian blinds are the most widely used in buildings at present due to its dynamically adjustable performance. Currently, more and more automatic venetian blinds control strategies have been developed to overcome the shortcomings of manual operation. It is also necessary to find the optimal shading control strategy to prevent indoor glare and to enhance the efficiency of energy saving. However, there is a lack of systematically review related to these research fields. This paper presents a review of the control strategies of the venetian blinds in various previous studies and analyzes the effects of different control strategies on indoor daylighting, glare prevention, thermal comfort and energy consumption. The review identifies current challenges and provides significant theoretical guidance for future research. At the same time, it also provides building design professionals with suggestive strategies and concepts of pre-shading design.

Keywords Automatic control strategies · Venetian blinds · Glare prevention · Energy saving

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1 Introduction

Daylighting in buildings has been demonstrated to significantly improve human performance, such as visibility, mood and health as well as productivity [1]. What's more, studies show that daylighting can reduce artificial lighting consumption from 50 to 80% [2]. However, excessive and uncontrolled daylight admission into a building can lead to visual discomfort, indoor overheating, and thus cause higher energy consumption for cooling and heating demands. To address this problem, a shading system is essential to block the direct sunlight and offer a comfortable indoor environment. The shading device types of buildings can be roughly divided into two categories: fixed shading devices(e.g. overhangs and louvers),movable shading devices (e.g. roller shades and venetian blind) [3]. The study conducted by Martin Vraa et al. [4] has proved that dynamic solar shading dramatically improves the amount of daylight available compared to fixed solar shading, and the venetian blind provides better average indoor illumination level compared to the roller shades [5]. The venetian blinds were broadly used in previous studies due to its' flexible adjustability. But the operation methods of it can heavily influence the performance both of daylighting and energy saving. In case of manual blinds, occupants tend to fully open or close the blinds and make little attempt to change the blinds position during the day [6]. This scenario often leads to higher energy demands and inability to access outdoor views [7]. This issue can be resolved with the use of automated blinds systems since they can adjust automatically by an appropriate control algorithm.

Generally, control strategies of blinds can be divided into open loop and closed loop control systems. Closed loop system receives feedback, whereas open loop does not [7]. The aim of the blinds control is to remain the indoor environment comfort, overcome glare and heating problems, thus to reduce energy demands, which can be achieved by blind height and slat angle control. In addition, the integrated automatic blinds and artificial lighting control strategies can help to reduce the energy demands for artificial lighting, cooling and heating and save up to 30–80% energy consumption [8, 9]. The automated control strategies of blinds are a crucial means to mitigate building energy consumption by daylight. Over the years, many researchers have done a lot of studies in this field by theoretical analysis and software simulation. This paper provides an overview of previous studies that have been done related to automatic control strategies of blinds and effects of different control strategies on indoor daylighting, glare prevention and energy consumption. Besides, this study will also benefit building design professionals when concepts of pre-shading are integrated with their design process.

2 Theory

2.1 Physical Sensors

An appropriate control strategy of blinds to ensure indoor environment comfort is designed according to weather condition, indoor illuminance data and other factors. Thus, various sensors that measure the sky information and indoor data are required. Most of the automatic control strategies of blinds require at least one sensor to predict daylight information.

Indoor sensor such as photosensor is usually amounted on the ceiling or window to provide indoor environment information for controller to make the appropriate decisions. In some studies [10–12], indoor illuminance sensors are used to measure the workplane illuminance levels or vertical eye illuminance and the data from sensors was as input variables for control algorithm.

Outdoor sensors are usually installed on the facade of the building to measure sky information. Kinds of sensors have been designed and used in practice by researchers, including sky scanner [13], sun angle sensor, digital camera, pyranometer meter [14], outdoor photosensor etc. Sky scanner is a very accurate instrument to measure luminance and radiance of sky, but the utilization rate is low due to its high price and difficult availability in the market. Sun angle sensor developed by LBNL determines the sun's altitude when the sun is in the plane of the window whether direct sun is present [15]. The sun angle sensor is usually used along with other sensors because it blocks direct sunlight and cannot determine daylight illuminance. However, the study conducted by Borowczyński et al. [16] has shown that a digital camera alone as a single sensor can be used for blinds control without taking any photometric measurements. Most frequently used sensors are outdoor photosensor as well as pyranometer meter to measure solar irradiance used mainly for cut-off strategy [7]. All types of sensors need to be calibrated to ensure accurate and reliable measurements.

2.2 Important Control Variables

Blind controllers have either been time dependent, or have been based on a threshold value [17]. In many references, various control variables of the blinds were suggested such as the solar irradiance, vertical illuminance and glare index. The venetian blinds can adjust the slats to a specific angle at a certain threshold value [18]. More sophisticated controller that includes more than one variable was proposed so that the state variables provide enough information to set the blinds in an optimal position for a given environment. However, Daum and Morel [17] pointed out that two state variables provide sufficient information for a good blind controller and more than three variables yields in no further improvement in the performance. The control variables of the blinds are one of the most important factors and are introduced in the followings.

2.2.1 Solar Irradiance and Position

Solar irradiance is a key factor that affects the blinds closing behavior of occupants. Gunay et al. [19] reported that when the solar irradiance is lower than 50 w/m^2, the shading system usage rate is once every 20 h occupancy, while above 800 w/m^2, the return period becomes once every 3 h or less. In another study, the blinds are activated when the solar vertical irradiance exceeds 100 w/m^2 [20]. Additionally, the solar position information (e.g. solar profile angle, and solar azimuth) is also used in blinds control algorithm to determine blinds height and slat angle. The control strategy against direct sunlight was basically based on solar position information [21], and the most widely used cut-off strategy was designed based on the solar profile angle [22].

2.2.2 Glare Index

Visual comfort is always the priority of venetian blinds control. An important factor affecting visual comfort is glare, and thus most blind control strategies regard the glare prevention as an important control objective. There are various metrics that quantify glare, such as Daylight Glare Index (DGI) [23], Predicted Glare Sensation Vote (PGSV) [24] and Daylight Glare Probability (DGP) [25], which are used for blind control in previous studies.

DGI is the ratio of source luminance to background and window luminance. A DGI value greater than 31 indicates unbearable glare, and less than 18 stands an almost imperceptible glare index. In some studies [10, 23, 26], the activation threshold value of DGI for the automatic blinds controller is always set to 22. PGSV is proposed by Iwata et al. [24] to predict the glare sensation vote. The values of PGSV are (0) just perceptible, (1) just acceptable, (2) just uncomfortable, (3) just intolerable [24]. A study conducted by Iwata et al. [27] developed an automated blinds control strategy based on glare prevention by using the PGSV as a control variable. To obtain PGSV, the average luminance of the window area is calculable, including blinds slats and the view from outside between the slats. The study has shown that the control method based on PGSV can reduce 30% of the lighting consumption, while providing view satisfaction around 46–50% during working hours. DGP is used to evaluate glare potential and describe the fraction of disturbed occupants under the specific daylight [25]. The value of DGP less than or equal to 0.35 is regarded to avoid discomfort. A study conducted by Konstantzos [28] has shown that DGP can potentially predict overestimated results for glare perception when sunlight falls on the occupant. To solve the problem, correction in the DGP equation coefficients was proposed by Konstantzos and Tzempelikos [29] when the sun is visible through the shades. The new glare discomfort index was developed based on direct and total-to-direct vertical illuminance on the eye.

2.2.3 Vertical Illuminance

Another parameter closely related to visual comfort is vertical illuminance, which is also an important metric to measure indoor glare. Konstantzos et al. [28] pointed out that the key factor in achieving visual comfort is the successful control of vertical illuminance, which is a parameter that may dramatically decrease glare without significantly affecting daylight availability. In a study conducted by Yun et al. [30] that Ev was recommended for the glare index, in place of the DGI or DGP, and the threshold value of Ev for avoiding glare is 3000 lx. However, in other studies, the value of Ev was suggested 2800 lx [29], while 1700 lx was also adopted [20]. The values can vary from different shading systems and variable conditions.

What's more, except vertical illuminance, workplane illuminance is also a control metric for indoor visual comfort which the threshold value usually set to be below 2000 lx for glare prevention. And the useful daylight illuminance (UDI), which is calculated based on workplane illuminance, is used to determine when illuminance levels are useful for the occupants [11, 31].

3 Automatic Control Strategies of Blinds

Venetian blinds, as the most commonly used shading devices, have been widely studied by researchers. The automatic control strategy is one of the most important concerns of researchers in previous research, since an appropriate control strategy can make a good balance between glare prevention and daylight utilization as well as energy savings. There are three categories of control algorithms depending on the control purpose and performance: (1) threshold controllers, where the blinds get activated when the threshold value limit is exceed; (2) sun blocking controllers, which adjust the blind height or slat angle to avoid direct sunlight; (3) mode and scene controllers, use a variety of sensors and different control algorithms [32]. The blind control strategies for indoor environment comfort and energy saving are discussed in the following part.

3.1 Cut-Off Control Strategy

The cut-off control strategy is the most widely used control algorithm of blinds that consider solar profile angle to cut direct sunlight all the time by rotating blinds slats [8, 10, 14, 20, 22, 27]. Cut-off angle is defined as the blinds tilt angle beyond which no direct radiation is being transmitted and the standard equation is as follows [33].

$$\beta_{cut-off} = 90^\circ - 2\Omega$$

where β is the tilt angle, the Ω is solar profile angle. There are two cut-off angles that exist for one solar profile angle, one towards the sky and another towards the ground [22].

Zhang and Birru [22] developed an open-loop control algorithm to avoid direct sunlight by calculating the cut-off angle according to solar profile angle. Although the cut-off strategy can avoid direct sunlight, studies have shown that this method is not sufficient to avoid indoor glare [33, 34]. Therefore, some researchers have proposed modified control algorithm, which can effectively avoid the occurrence of indoor glare. Chan and Tzempelikos [33] have pointed out that there may be the second reflection originating from the bottom surface of the slats when applying the "cut-off angle control". Thus, the "daylight redirection control" have been proposed as shown in Fig. 1, and the tilt angle that redirects light to the desired angle can be obtained by:

$$\beta_{design} = \frac{\delta_{design} - \Omega}{2}$$

where the δ is the outgoing "reflected" angle calculated by $\delta = \Omega + 2\beta$.

Iwata et al. [27] proposed a glare prevention control algorithm based on improved cut-off angle control strategy. When shading is required, the slat angle is set to cut-off angle, and the indoor glare is calculated by PGSV. Afterwards, the results are compared with the pre-set value. If the indoor glare exceeds the set value, additional angle is added until the glare level is below the set value. Similarly, Karlsen et al. [20] proposed a control strategy related to factors of glare, daylight sufficiency and view to outside. The control strategy focuses on avoiding glare by utilizing the estimated cut-off angle of the slats. Improvement has been made for the control strategy, which the tilt angle is step-wised increased in case the cut-off angle is insufficient in avoiding glare.

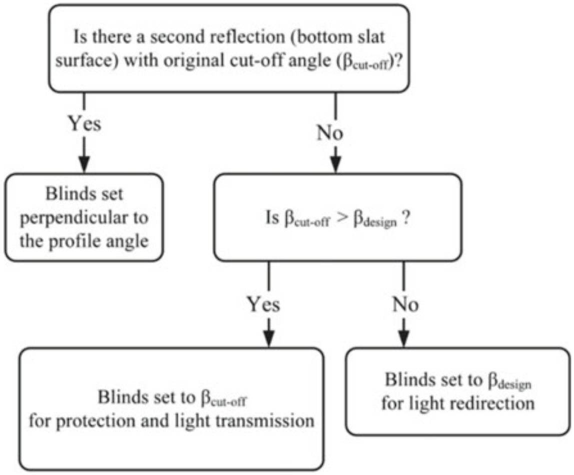

Fig. 1 Flowchart of light redirection control [33]

3.2 Control Strategy Considering Indoor Visual Comfort

3.2.1 Glare Control

Excessive daylight incidence in the room will increase the risk of indoor glare. Control strategy of blinds for glare prevention is crucial for visual comfort improvement. Generally, the commonly used glare control strategy quantifies the glare and then compares value with the pre-set threshold value, activating the blinds for glare protection if the threshold value is exceeded. Myung Hwan et al. [26] proposed an optimized control strategy of slat-type blinds based on solar radiance and DGI. Double-sided blind was adopted with different reflectance between front and back sides of the slat, the control strategy was developed by drawing the trend line between the slat angle and the solar radiation, and the slat angle of DGI greater than 22 are excluded. The results have shown that the control strategy can save 29.2% of total energy consumption and reduce the glare incidence to 0.1%.

Two glare control methods that consider sky conditions were proposed by Chan and Tzempelikos [33]. One of such control modes is shown in Fig. 2. The blinds are continuously controlled by using real-time DGP simulation. Several sensor readings and HDR camera-based measurements are required to simulate the glare index. And the other glare control strategy was developed based on annual pre-simulated results. The blinds are controlled to on/off position based on pre-determined correlations between transmitted illuminance and DGP. The "off" position is defined as to ensure the percentage of time during which DGP exceeds 35% is less than 5%. When the DGP values exceed the set point, blinds would rotate to the "off" position, otherwise, the slats would remain horizontal position.

A glare control algorithm presented in a study [10], first calculated the sky ratio according to the information of sun's position and global diffuse horizontal irradiance

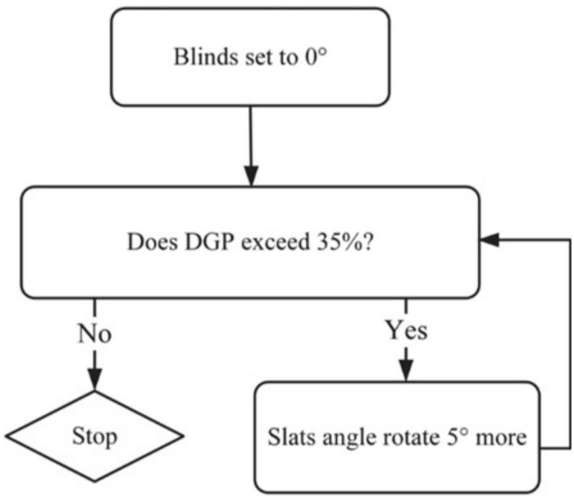

Fig. 2 Flowchart of glare blind control [33]

etc. The value of sky ratio higher than 0.8 indicates a cloudy day and the slats are set to be horizontal. Otherwise, slats are rotated to be cut-off angle and DGI is calculated. If DGI is greater than 22, slat angle increases till DGI becomes less than 22. The annual simulations have shown the DGI under 22 for the whole period of time.

3.2.2 Glare Control Based on Illuminance Levels

Indoor illuminance is also closely related to indoor visual comfort, and can also be used to measure the glare. In a study [30], the value of Ev was set to be 3000 lx as the threshold for glare control. In order to maximize the benefits of daylight in building, Young et al. [21] proposed a multiple blinds control strategy that can protect the area which defined by users from direct sunlight, to introduce more daylight into the room. Jia and Svetlana [31] proposed an illuminance-based slat angle selection model for automated control of split blinds, which are divided into upper, middle and lower parts and the slats of each part can be rotated to a different angle. The model was constructed based on artificial neural networks (ANNs), using weather determinants as input variables, then output the optimum slat angles. UDI was used as the illuminance metric to maintain the indoor illuminance between 500 and 2000 lx. The result has proved that the ISAS model has great performance in calculating the optimum slat angles. Subsequently, Jia and Svetlana [11] developed another split blind control strategy. The control method is divided into two control modes, covering view mode and daylighting mode. The control mode is selected firstly to monitor indoor illuminance below 2000 lx. The process of activating blind sections and opening the slats is repeated until the illuminance is less than 2000 lx while the slat angles for all the sections of blinds reach the limits.

3.3 Control Strategy Considering Thermal Comfort

The operation of the shading devices also has a significant impact on indoor thermal comfort. In a study [35], a solar control strategy with a critical angle which presents the incident rays perpendicular to the slat surfaces is proposed to reduce the solar heat gain of the shading system. The critical angle φ critical angle is calculated by

$$\varphi \text{ critical angle} = 90^\circ - \beta$$

where, β is the solar profile angle. When the solar profile angle is greater than the critical angle, the incident beam radiation will fully reflect.

Khang [36] developed a Model Predictive Control strategy of blinds in order to ensure the indoor thermal and visual comfort. The proposed method is based on Branch and Bound techniques and has the ability to anticipate the future evolution of indoor temperature. The control objective is to ensure the thermal comfort where a temperature upper bound is fixed at 26 °C, and to maintain a minimum illuminance level (300 lx) in the room for the visual comfort. However, this control strategy is difficult to apply to real life due to the limited computation capacity. Therefore, a logical controller was proposed, whose rules and parameters learn from the behavior of the MPC controller using support vector machine (SVMs) [37]. It can transform the complicated model predictive control into a simple rule-based control. Results shown that the performance of the approximate controller that can be easily implemented within a microprocessor product is very close to the MPC controller.

3.4 Integrated Blinds and Artificial Lighting Control Strategies

Automated blinds integrated with dimmable electric lighting system have been proposed more than 20 years ago [39]. Significant energy savings were observed by applying the integration of automated blinds with artificial lighting controls [40]. A full-scale experiment has been done, which investigates the performance of integrated blinds and dimmable lighting systems on energy saving [41]. The simulation results have also shown that the system can save more than 24% of electric lighting energy in every month of the simulated year, while maintaining illuminance at the workstation at the required level.

In some studies [42–45], some advanced mathematical algorithms, such as fuzzy logic algorithms and artificial neural networks, are applied to automatic control algorithm of blinds. By means of two-dimensional fuzzy control algorithm, an integrated blinds and electric lighting system was proposed [42, 43]. The blinds angle is determined by the controller with input variables which is the difference between the indoor illuminance value and the pre-set value (workplane illuminance is set to 500 lx). If the slat angle of venetian blinds reaches the limit, while the indoor illuminance still cannot meet the set value, then the artificial lighting mode is turned on.

Guillemin and Morel [46] developed an innovative and self-adaptive integrated system that combines lighting and shading controls for building energy and comfort management. The control algorithm is called sun-position determines blinds position by considering the height and azimuth of the sun as well as the inside horizontal illuminance. And the artificial lighting controller is used to complete the illuminance in the room up to the desired level. The integrated system can reduce 25% total energy consumption compared to a conventional one. Gunay [19] analyzed the light-switch and blinds use behaviors in ten private offices and developed an adaptive blind and lighting control algorithm. The control algorithm was implemented in a controls laboratory and five West-facing private offices, and the results indicated that it could reduce 25% electric lighting consumption without adversely affecting the user's comfort. In addition to the integration of electric lighting and blinds control systems, there are few studies quantified the benefits of sharing control information (e.g., HVAC state and occupancy information) between the lighting and shading

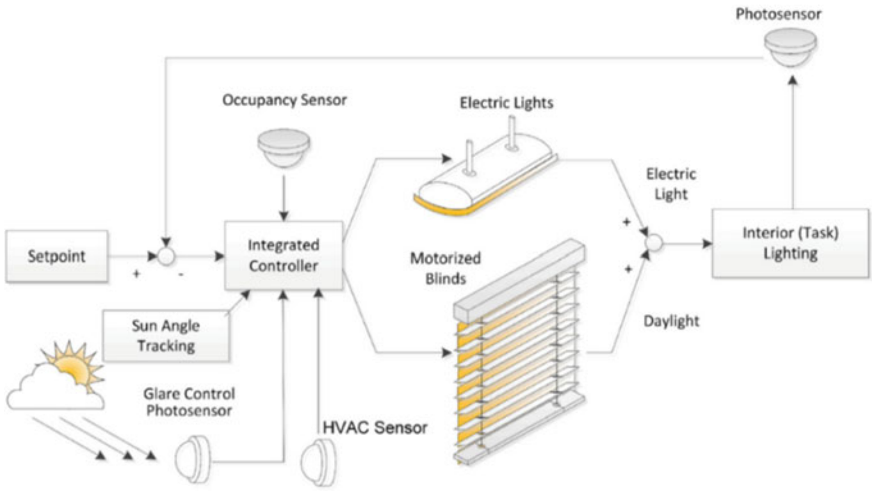

Fig. 3 Integrated lighting and daylight control [38]

control systems. Shen et al. [38] proposed an improved independent and integrated control strategies by adding shared HVAC state and occupancy information, as shown in Fig. 3. The lighting, heating and cooling energy consumption, electric demand and visual comfort of seven control strategies (i.e., four independent, two integrated, and one manual control system) were evaluated and compared. Results have shown that integrated lighting and daylight control outperforms all other strategies in energy and visual comfort performance.

3.5 Control Based on occupant's Usage Pattern

Although the automatic shading control systems can provide occupants with good visual comfort, while saving the total energy consumption of the building, at the same time, it will also reduce the occupants' perception of control over the environment. Galasiu and Veitch [47] pointed out that the occupants' preference to have the capability to choose their environment rather than being obligated to accept the environment chosen for them. Other studies [39, 48]also confirmed that the occupants' satisfaction with semi-automatic shading system improved with an increasing ability to control the indoor illuminance levels. Occupants tend to switch off the automatic system or adjust the action which the automatic mode makes. One of the reasons was that occupants did not understand why the blinds were moving up or down. To help people understand and accept the behavior of automated systems, an expressive interface was designed to communicate the status and intentions of the blinds system to the occupants [49]. The light feedback system was designed to be mounted on the top of a blinds system and the example of its respondence in different situations

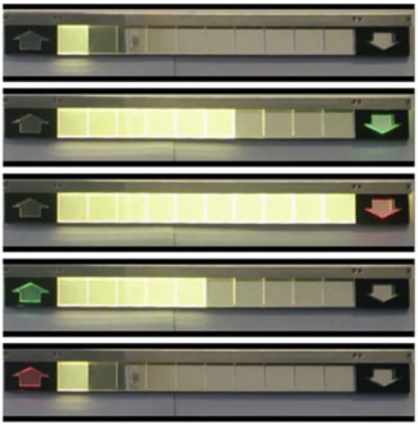

Fig. 4 Example of light feedback in different situation [49]

is shown in Fig. 4. The results demonstrated the potential of expressive interfaces to increase user's acceptance of automated blinds to realize the anticipated energy savings.

Sadeghi et al. [50] performed a comparative study on occupant interactions with different environmental controls ranging from fully automated to fully manual and interfaced with low or high level of accessibility (wall switch, remote controller and web interface). The study further indicated that an easy-to access control interface is significant for improving the occupants' satisfaction with the automatic shading systems. Subsequently, researchers [51] proposed an energy-efficient controller for shading devices self-adapting to the user's wishes. The adaptation process is composed of three distinct modules: a wish pre-processing module, the GA engine module and a sensitivity filter. The system has been tested with several sets of synthetic wishes and shown a powerful ability to 2nd satisfactory solutions, even with complex combinations of wishes.

4 Conclusion

This paper provides an overview on the automatic control strategies of blinds. The frequently used indoor and outdoor sensors have been discussed, as well as the important control variables in control algorithms. Table 1 summaries the automated control strategies of blinds considering indoor environment comfort and energy saving. Some advanced mathematical algorithms and technologies have been applied to the automated control strategies of blinds. And both field experiment and software simulation have been used to evaluate the performance of the blinds control strategies. In term of the reviewed studies, current knowledge can be expressed as the followings:

Table 1 Automated control strategies of blinds used in literature

S. No.	Control methods	Control objective	Input variables	References
1	Cut-off control strategy	Visual and thermal comfort, Energy saving	E_v, Vertical irradiance, Solar profile angle	[10, 20, 22, 27, 33]
2	Control based on illuminance levels	Maximize daylight efficiency	UDI, vertical illuminance	[11, 14, 21, 31]
3	Control based on glare index	Glare prevention	PGSV, DGI, DGP, E_v	[10, 26, 27, 30, 33]
4	Integrated control with blind and electric lighting	Electric energy saving	Indoor sensors signal, Solar radiation	[8, 10, 19, 26, 27, 38, 39, 41, 46, 52]
5	Control based on occupant's pattern	Occupant's satisfaction	Occupant's wishes	[19, 39, 47, 49–51]

- Automatically controlled shading systems have potential to improve indoor environment comfort and reduce energy consumption for building.
- One of the main challenges to achieve the optimal automatic blinds control strategy is to accurately estimate the rapidly changing sky conditions. In order to accurately evaluate the sky condition, sensors of different types and functions are required and the calibration of sensors is particularly important. However, it has been reported that the reliability of the sensor is low in cloudy and direct sunlight weather. On the other hand, the complexity and expensive price of the sensor is one of the main obstacles that affect the extensive application of automatic control strategy in real life.
- The aim of automated control strategies of blinds is to improve the indoor environment comfort and reduce energy consumption, which can be achieved by blinds height control and slat angle control, while the indoor visual comfort is usually a priority, especially for glare prevention. And the integration of blinds with electric lighting system is proved to have large potential for energy saving.
- The user's acceptance and satisfaction with the automatic control strategy determined whether the shading systems could exert its maximum performance in the building. Occupant override authority or manual control interface should be remained to enhance the occupant's perception of control to improve the blinds utilization.

As far the reviewed papers are concerned, some of the current automatic blinds control strategies are difficult to apply to reality due to the complexity of control programs. Additionally, many automatic control methods mainly focused on indoor comfort and energy consumption, but few studies considered the view to outside in blinds control strategies. Studies have shown that occupants may extend the tolerance levels towards discomfort glare if pleasant view were present [53]. Another research also reported that view to the outside influenced the choice of preferred control strategy [34]. According to these review findings, the future research will go further as the followings:

- Some advanced techniques and algorithms require to further explore to decrease the difficulty of the application of automatic blinds control strategies. Develop commercial deployable and extensible working prototype of the system, and improve the application and performance of the automatic blinds system.
- Algorithm for speeding up the control process and timely reaction of the control system. Such as machine learning, which can greatly improve the operation speed and accuracy of automatic control algorithm.
- The integration of simulated daylight metrics with control systems is worth further research and exploration. Advanced simulation assisted control introduced an innovative solution for integrated blind and lighting control, integration of real-time daylight information into the simulation model, which can minimize the use of sensors through simulation, solve the problem of high sensor price, and also obtain the benefits of energy saving and visual comfort.
- The automatic control strategies of blinds should consider the provision of external view while achieving indoor environment comfort and energy saving.
- The relationship between user's behavior pattern and automated control strategies of blinds requires further research to prompt the occupant's acceptance and satisfaction of automated control blinds system. And the post occupancy surveys are needed.
- Global analysis of building combined with daylighting and thermal environment. Light and heat are interrelated and affect each other, which together determine the overall indoor environmental comfort. It is not enough to study one aspect alone, sometimes could be also misleading.

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