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System for Responsive Daylight Control with a Motorized Window Covering

Abstract

Disclosed is a system for responsive daylight control using an electronically actuated shading device. Optionally, the system has a longer response time in opening the shading than in closing the shading. Optionally, the system inhibits opening of the shading device in the presence of a fluctuation in the daylight level. Optionally, the response time in opening the shading is increased when the system is powered by a battery and/or with decreasing battery charge.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] I hereby claim benefit under Title 35, United States Code, Section 119(e) of U.S. provisional patent application Ser. No. 63/596,255, filed Nov. 4, 2023, and U.S. provisional patent application Ser. No. 63/512,065, filed Jul. 5, 2023, which are currently pending as of the filing of this application.

PRIOR ART

[0002] This disclosure cites the following non-patent prior-art references: [0003] M. Anvari, G. Lohmann, M. Wächter, P. Milan, E. Lorenz, D. Heinemann, M. Reza Rahimi Tabar, and Joachim Peinke (2016). Short term fluctuations of wind and solar power systems. New J. Phys. Volume 18. 063027. https://doi.org/10.1088/1367-2630/18/6/063027. [0004] J. M. Bright, C. J. Smith, P. G. Taylor, R. Crook (2015). Stochastic generation of synthetic minutely irradiance time series derived from mean hourly weather observation data. Solar Energy, Volume 115, 229-242. https://doi.org/10.1016/j.solener.2015.02.032/. [0005] E. S. Lee, D. L. DiBartolomeo, E. L. Vine, Ph. D., and S. E. Selkowitz (1998). Integrated Performance of an Automated Venetian Blind/Electric Lighting System in a Full-Scale Private Office. LBNL-41443, Lawrence Berkeley National Laboratory, California USA. [0006] Mohammed Olama, Jin Dong, Isha Sharma, Yaosuo Xue, and Teja Kuruganti (2020). Frequency Analysis of Solar PV Power to Enable Optimal Building Load Control. Energies 2020, 13, 4593. https://doi.org/10.3390/en13184593

BACKGROUND OF THE INVENTION

[0007] This invention is in the field of automated window-shading systems, and specifically systems employing motorized window coverings and which are capable of automatically controlling admitted daylight in response to changing conditions.

[0008] Systems which automatically adjust a window-shading device to one of two fixed settings (e.g. opened and closed), in response to changing conditions, have been available for decades. Such systems include those which provide automatic “open at dawn, close at dusk” operation, and those which automatically close in the presence of direct sunlight (typically sensed as a rise in temperature). Because the adjustments are between only two shading settings, they provide only coarse regulation of the admitted daylight.

[0009] A more sophisticated form of automated shading is one which adjusts the shading whenever and as much as necessary to regulate the admitted daylight. Such a capability is referred to herein as responsive daylight control.

[0010] It is well-known in the art that responsive daylight control can significantly increase the average level of glare-free natural illumination in indoor spaces when compared to manual control or other forms of automated shading. That, in turn, can provide a healthier and more appealing visual environment, while also increasing the energy savings achievable through daylight-harvesting lighting strategies.

1.0 Smart Windows Versus Motorized Window Coverings

[0011] Dynamic glazing technologies enable so-called Smart Windows, which offer adjustable shading without moving parts. However, Smart Windows with continuously-variable shading (as needed for responsive daylight control) are not yet cost-effective for mainstream use.

[0012] Therefore, motorized window coverings are currently the only viable option for a mainstream responsive daylight-control capability. Window covering amenable to motorization for this purpose include curtains, venetian blinds, and roller shades.

2.0 Obstacles to Responsive Daylight Control with Motorized Window Coverings

[0013] Implementing a responsive daylight control system with a motorized window covering presents a dilemma: the system should be responsive enough to quickly block glare and admit useful daylight when there is no risk of glare, and yet it should not respond to rapid fluctuations in solar irradiance (e.g. due to cloud movement) that would otherwise result in frequent high-amplitude shading adjustments.

[0014] If the system fails to respond reasonably quickly to significant changes in the daylight level, then the system will provide little benefit over conventional automated shading. On the other hand, if it makes frequent, high-amplitude shading adjustments, its operation will be obtrusive and its mechanical lifetime (and, if battery-powered, its battery life) will be reduced.

[0015] The prior art provides no effective solution to this dilemma, which remains a significant obstacle to mainstream deployment of responsive daylight control technology.

3.0 Prior-Art Approaches to Overcoming the Obstacles

[0016] Practical implementation of responsive daylight control was first addressed at Lawrence Berkeley National Laboratory (LBNL) in the U.S. in the 1990's. Despite being decades old, the techniques developed over the course of that research still represent the current state-of-the-art in overcoming the obstacles described above. A resume of those techniques is given in the referenced 1998 paper by Lee et al at Lawrence Berkeley National Laboratory (LBNL). In general, these techniques fall into two categories: those aimed at reducing the obtrusiveness of shading adjustments, and those aimed at trading-away system responsiveness to minimize the frequency of shading adjustments.

3.1 Prior-Art Approaches to Reducing Obtrusiveness of Shading Adjustments

[0017] Two approaches have been used to reduce the obtrusiveness of shading adjustments made by responsive daylight control systems that incorporate motorized window coverings: the choice of a motorized horizontal blind as the shading device, and the use of low-duty-cycle pulsed motor operation to make the blind operation less obtrusive.

3.1.1. Use of Motorized Horizontal Blind

[0018] Horizontal venetian blinds offer two modes of adjustment: adjustable slat tilt and raising/lowering of the slats. The adjustable slat-tilt function is particularly well-suited for responsive daylight control because it provides excellent control of the admitted daylight, can be motorized with a relatively small and quiet motor, and is relatively unobtrusive in operation. No other type of mechanical shading device offers these advantages.

[0019] Accordingly, LBNL's prototype responsive daylight-control system employed a horizontal blind with motorized slat-tilt capability.

[0020] Even today, the horizontal blind with motorized slat-tilt offers the least obtrusive operation of any cost-effective shading device suitable for responsive daylight control.

3.1.2 Use of Low-Duty-Cycle Pulsed Motor Operation

[0021] When a motorized blind is actuated via a user interface (e.g. a wireless remote control), users expect shading adjustments to be completed within a few seconds.

[0022] On the other hand, while automatic shading adjustments for responsive daylight control should ideally be initiated quickly in response to the onset or cessation of glare-inducing conditions, the adjustments themselves need not be as rapid as for manual adjustments.

[0023] This fact can be exploited to reduce the obtrusiveness of automatic adjustments by reducing the motor speed. If a DC gearmotor is used, its speed can be reduced—while still maintaining the required torque—via variable-duty-cycle pulsed operation. The LBNL researchers recognized this in the above-referenced paper (Lee et al, paragraph entitled “Motor”, page 6): [0024] “Because the motor with gear train produced a small, high-pitched sound, modifications were made to reduce both the sound level and the frequency and speed of blind movement. As designed, the miniature high-speed, low-cost DC blind motor was geared down to deliver sufficient torque to operate the blind apparatus. A change in blind angle of about 5° required a DC pulse of approximately 50 ms, which resulted in a quick twist of the blinds which was visually distracting. The motor speed could be reduced by decreasing the supply voltage, and therefore torque, but this would cause the blind to stall under high load conditions (e.g., when closed). Instead, we modulated the duty cycle of the applied DC power to deliver more power when needed to maintain blind movement. A pulsed DC power source at a frequency of ˜100 Hz with a variable duty cycle was used to power the motor for a fixed pulse duration. The rate of blind angle change was reduced by a factor of four while not causing a stall in movement at high loads. In addition, the motor noise was reduced to a soft ticking similar to that of a small clock. Additional noise control can be achieved by placing the motor in a sound-dampening housing."

[0025] Such pulsed operation also offers another advantage for responsive daylight control: it allows time between the pulses for sensor sampling and calculations, e.g. as needed for some approaches to closed-loop daylight control.

3.2 Prior-Art Approaches to Trading-Away System Responsiveness

[0026] The most straightforward approach to minimizing the obtrusiveness of responsive daylight control is to simply reduce its responsiveness to changing daylight levels, thereby reducing the frequency of shading adjustments. In the above-referenced paper, LBNL researchers state the following (Lee et al, paragraph entitled "System Design", page 5): [0027] "A very responsive window system may meet all control objectives adequately, especially under transient conditions (partly cloudy skies), but large angle and/or frequent blind movement may cause distraction. Our default setting was activation every 30 s with unlimited blind movement. We parametrically tested a number of algorithms that changed 1) the interval of activation and 2) the amount of change in blind angle within an interval of activation. We also tested "smarter" algorithms that incorporated time delays before a blind could reverse the direction of movement to avoid hunting and oscillations that can occur during partly cloudy conditions."

[0028] Solar irradiance can fluctuate with a period shorter than 30 seconds, so LBNL's choice of a 30-second default activation interval already compromised some control responsiveness for less distracting operation. The other algorithms were aimed at further reducing the system's responsiveness in an attempt to find the optimum balance between responsiveness and unobtrusiveness of operation.

[0029] However, Lee at el recognized that the techniques investigated were not always sufficient to achieve an acceptable compromise between responsiveness and unobtrusiveness of operation. In the section titled CONTROL SYSTEM PERFORMANCE, Blind Movement (page 11), they state: [0030] "On occasion, the blind reversed direction or moved significantly within a short period of time in a manner that may be perceived as distracting. With 30-s blind activation, the blind was moved more than 10° total in any direction within 5 min on average 53 times per day (7% of a 12-h day) throughout the year, with a maximum of 234 times occurring on a partly cloudy summer day. The blind reversed direction at least twice within a 2-min period an average of 12 times per day (1.6% of a 12-h day) throughout the year, with a maximum of 70 times occurring also on a partly cloudy day. The tally may be lower than actual because the blind was activated every 30 s while data was recorded every 60 s. Contiguous movement for more than 10 min will result in a higher tally than if non-contiguous." [0031] "Unnecessary movement can be reduced with smarter control algorithms that accommodate temporary environmental changes. We designed and tested a number of blind algorithms that lengthened the activation cycle, restricted angular movement per activation cycle, and/or delayed angular movement in the opposite direction. In FIG. **9**, we compare blind operation on a partly cloudy day if blind movement is not permitted within 15 min of the last time it was moved. In FIG. **10**, we compare blind operation if blind movement in the opposite direction is not permitted within 15 min of the last time it was moved. In each case, control objectives were not met as consistently, fluorescent lighting use increased, but movement was reduced which may lessen potential occupant distraction. System longevity may also be increased. Drawbacks include less stability in interior illuminance levels and periodic direct sun. Lighting and cooling energy reductions may also be affected (see energy section below). Design improvements to the blind's motor system over the year resulted in very quiet and smooth motion, which may lessen the importance of these control refinements. User adjustment of blind activation settings may also increase occupant satisfaction."

[0032] In short, by applying the above-described techniques, the LBNL researchers were able to reduce the obtrusiveness of system operation—but not completely, and not without significant compromise in the effectiveness of daylight control provided by the system. In particular, they noted (page 12) that “drawbacks include less stability in interior illuminance levels and periodic direct sun.”

3.3 Summary of Prior-Art Limitations

[0033] In summary, while decades have passed since LBNL's development of the first responsive daylight control systems, the problem of achieving adequate responsiveness without obtrusive operation remains unsolved. Specifically, prior-art approaches for solving this problem suffer from one of two limitations: [0034] a. excessively long response time to the onset or the cessation of glare-inducing conditions, thereby either exposing building occupants to daylight glare or reducing useful natural illumination (and thereby weakening the value proposition for responsive daylight control); or [0035] b. frequent, high-amplitude shading adjustments, which engender occupant dissatisfaction and reduce system operating lifetime (as well as battery life for battery-powered systems).

[0036] These limitations have been a significant factor in the failure of responsive daylight control to gain mainstream commercial acceptance.

OBJECT OF THE INVENTION

[0037] It is therefore an object of the invention disclosed herein to enable a responsive daylight control capability which responds quickly to the onset and cessation of glare-inducing conditions, and yet which avoids excessively frequent shading adjustments.

[0038] Further objects and advantages will become apparent from a consideration of the drawings and accompanying description.

SUMMARY OF THE INVENTION

[0039] The subject invention is a system for responsive daylight control using an electronically actuated window-shading device. The system includes a means of obtaining a daylight signal which depends on the daylight level and a controller to open the shading device with decreases in the daylight signal and to close the shading device with increases in the daylight signal. Optionally, the controller has a longer response time in opening the shading than in closing the shading. Optionally, the system includes a means of inhibiting the opening of the shading device in the presence of a fluctuation in the daylight level. Optionally, the response time in opening the shading is increased when the system is powered by a battery and/or with decreasing battery charge.

[0040] By optionally having a shorter response time in closing the shading than in opening the shading, the system is able to quickly respond to glare-inducing conditions while still limiting the frequency of shading adjustments. By optionally inhibiting the opening of the shading device during daylight fluctuation, the system can have a shorter response time during periods without daylight fluctuation while still limiting the average frequency of shading adjustments. By optionally increasing the response time in opening the shading when under battery power, and optionally with decreasing battery charge, the system can extend battery lifetime while still providing responsive daylight control.

[0041] The system thereby provides a better balance of responsiveness and unobtrusive operation than prior-art approaches to responsive daylight control. Further, it can be implemented through software modifications to conventional daylight-control systems, and is therefore amenable to integration in a wide range of systems capable of automatic daylight control.

Description

BRIEF DESCRIPTION OF DRAWINGS

[0042] FIG. **1** shows a high-level block diagram of an exemplar preferred embodiment of a

responsive daylight-control system.
[0043] FIG. **2** shows a flowchart of the software operating steps performed by the system of FIG. **1** while the shading is not being adjusted.
[0044] FIG. **3** shows a flowchart of a dual-time-constant filter according to the subject invention.
[0045] FIG. **4** shows a flowchart of operating steps incorporating the dual-time-constant filter of FIG. **3**.
[0046] FIG. **5** shows a flowchart of alternative operating steps to implement an asymmetric response time in shading-control logic.
[0047] FIG. **6** shows a flowchart of operating steps to indirectly inhibit shade opening in the presence of daylight fluctuation.
[0048] FIG. **7** shows a flowchart of operating steps to directly inhibit shade opening in the presence of daylight fluctuation.
[0049] FIG. **8** shows a flowchart of a daylight fluctuation detector using broadband amplitude demodulation.
[0050] FIG. **9** shows a flowchart of a daylight fluctuation detector using band-limited amplitude demodulation.
[0051] FIG. **10** shows a flowchart of a daylight fluctuation detector using band-limited amplitude demodulation via the Goertzel algorithm.
[0052] FIG. **11** shows a flowchart of a daylight fluctuation detector implemented using a weather-service Application Programming Interface (API)
[0053] FIG. **12** shows a flowchart of operating steps to implement an asymmetric response time and to indirectly inhibit shade opening in the presence of daylight fluctuation.
[0054] FIG. **13** shows a flowchart of operating steps to implement an asymmetric response time and to directly inhibit shade opening in the presence of daylight fluctuation.
[0055] FIG. **14** shows a block diagram of a responsive daylight-control system with a configurable power source.
[0056] FIG. **15** shows a flowchart of operating steps to implement a shade-opening response time dependent on the type power source.
[0057] FIG. **16** shows a block diagram of a responsive daylight-control system with a battery power source.
[0058] FIG. **17** shows a flowchart of operating steps to implement a shade-opening response time dependent on battery charge.
[0059] FIG. **18** is a function block diagram of logic to enable slow-response shade opening in sustained daylight fluctuation.
[0060] FIG. **19** is a flowchart of operating steps associated with determining a low-pass filtering time-constant as a function of the presence of fluctuation and the sign of changes in the daylight level.
[0061] FIG. **20** shows a functional block diagram of logic to enable a reduced release time after isolated fluctuations.

DETAILED DESCRIPTION OF THE INVENTION

1 Convention Regarding Special Terms and Variables

[0062] Italicized but un-bolded text is used herein for the first use of special terms whose meanings are defined in the LIST OF SPECIAL TERMS. Italicized and bolded text are used herein for variables and parameters.

2 List of Special Terms

[0063] Amplitude demodulator: A means of obtaining an output signal which depends on the amplitude or magnitude of a time-varying input signal.
[0064] Closing (of shading device): An adjustment of a window-shading device that tends to increase the shading of the window and, therefore, reduce the daylight admitted by the window.
[0065] Daylight level (level of daylight): A quantity which depends on the daylight illuminance on

the outward-facing side of a window-shading device, and which-depending on context-could refer either to daylight which is incident on the outward-facing of the shading device, or to daylight which is admitted into a room by the shading device.
[0066] Fluctuation (of daylight): A non-monotonic temporal variation of the daylight level.
[0067] Fluctuation detection: Detection of ongoing or imminent fluctuation of daylight, either directly by sensing fluctuation in an analog of the daylight level (e.g. the output signal of a daylight sensor), and/or indirectly by sensing conditions correlated with fluctuation (e.g. weather conditions correlated with moving clouds).
[0068] Fluctuation spectrum: The frequency content of fluctuation, e.g. as represented by the amplitude-spectral-density, power-spectral-density, or energy-spectral-density of a signal representing the fluctuation.
[0069] Non-problematic fluctuation: Fluctuation which can be compensated via automatic adjustment of a shading device without annoyance to building occupants.
[0070] Opening (of shading device An adjustment of a window-shading device that tends to decrease the shading of the window and, therefore, increase the daylight admitted by the window.
[0071] Opposing-adjustment interval: The interval between shading adjustments in opposite directions (e.g. between closing and opening, or between opening and closing adjustments).
[0072] Problematic fluctuation: Fluctuation which, if compensated via automatic adjustment of a shading device, would result in a pattern of shading adjustments which is annoying to building occupants.
[0073] Response time (of responsive daylight-control system): In a responsive daylight-control system, the delay between the beginning of a change in the daylight level and the resulting automatic shading adjustment, if any. The shade-closing response time is the interval between the beginning of an increase in the daylight level and the resulting closing of the shading device, while the shade-opening response time is the interval between the beginning of a decrease in the daylight level and the resulting opening of the shading device.
[0074] Software: A set of instructions or operations executed by a programmable device (including what is generally referred to as firmware).

3 Introduction

[0075] To facilitate a complete understanding of the subject invention, this section first addresses requirements for effective responsive daylight control before proceeding to a description of preferred and alternative embodiments.

4 Requirements for Responsive Daylight Control

[0076] Development of the subject invention was preceded by extensive testing of responsive daylight-control systems using motorized horizontal blinds. The testing confirmed certain long-standing assumptions about occupant-friendly responsive daylight control while contradicting others, and revealed three key requirements (in order of descending importance): [0077] a. The maximum acceptable response time in blocking severe daylight glare is only a few seconds. [0078] b. The minimum acceptable interval between shading adjustments in opposite directions (hereinafter referred to as the minimum acceptable opposing-adjustment interval) is much longer (typically at least several minutes and often more than ten minutes, depending on the occupant). On the other hand, there is little correlation between occupant satisfaction and the minimum interval between shading adjustments in the same direction. [0079] c. Subject to the above constraint, the system should be as responsive as possible to falling daylight levels. This is because, while a long delay between the cessation of glare-inducing conditions and opening of the shading will not distract or annoy occupants, it will decrease both the actual and perceived benefit of responsive daylight control.
[0080] The subject invention enables these requirements to be met to a greater degree than is possible with conventional responsive daylight control systems.

5 Overview of Subject Invention

[0081] The subject invention, informed by the results of the testing described above, incorporates one or both of two innovations in the form of algorithms implemented with conventional daylight-control hardware: [0082] a. An asymmetric response time to changing daylight levels, such that the system reacts more quickly to close the shading in rising daylight levels than to open the shading in falling daylight levels. Optionally, the response time to falling daylight levels is increased when the system is operating under battery power and/or as the battery charge is depleted, in order to maximize battery life. [0083] b. Inhibition of shade-opening adjustments during problematic daylight fluctuation.

[0084] When implemented alone, each of these innovations enables significantly higher levels of occupant satisfaction than when the same hardware is used to implement conventional responsive daylight-control algorithms. The innovations are complementary, such that combining them leads to still further increases in occupant satisfaction.

[0085] Each of the innovations (and combinations thereof) offers a different balance of simplicity and effectiveness, and might therefore be preferred over the others in a particular application.

6 Overview of Disclosure

[0086] Since the subject invention can be implemented with conventional responsive daylight-control hardware, this disclosure begins with a high-level description of a responsive daylight-control system that applies to conventional systems as well as to preferred embodiments of the subject invention. Preferred embodiments of the subject invention are then described as modifications to, or lower-level details of, the initially-described high-level configuration.

7 FIG. **1**: High-Level Block Diagram of Responsive Daylight-Control System

[0087] FIG. **1** depicts a high-level block diagram of a responsive daylight-control system **10** according to the subject invention. At this high level, the block diagram shown in FIG. **1** is also representative of conventional responsive-daylight-control systems.

[0088] System **10** includes conventional daylight-sensing means **11**, a conventional controller **12**, and a conventional electronically actuated window-shading device **13**. Shading device **13** is mounted on a window in a room (not shown). The purpose of system **10** is to automatically actuate shading device **13** to regulate the daylight admitted by shading device **13** into the room.

[0089] As with conventional responsive daylight-control systems, system **10** will typically include other conventional elements such as those required to implement a power supply or a user-system interface. Such conventional elements are incidental to responsive daylight-control in general, as well as to the embodiments of the subject invention to be described in reference to FIG. **1**, and are omitted for the sake of clarity.

[0090] As with conventional responsive daylight-controls systems, the elements of FIG. **1** need not be physically collocated. For example, shading device **13** can be attached to a window in a room, sensing means **11** can be mounted on the roof the building containing the room, and controller **12** could be “in the cloud”, i.e. in a remote server. Conversely, all of the elements of FIG. **1** can be physically collocated in a single package, e.g. attached to a window.

7.1 Daylight-Sensing Means **11**

[0091] Daylight-sensing means **11** is a conventional means of producing a daylight signal which depends, directly or indirectly, on the daylight illuminance on the outside of the window on which shading device **13** is mounted. Such means could be, for example, an electro-optical sensor sensitive to a wavelength in the daylight spectrum (whether visible or invisible), a temperature sensor, a current sensor to monitor the output current of a photovoltaic panel, or an interface to obtain a daylight signal from an external source. In the preferred embodiment, daylight-sensing means **11** is a light-sensing integrated circuit which incorporates a photodiode, an analog-to-digital converter, and a serial interface to produce the daylight signal in digital form.

[0092] Daylight-sensing means **11** can be used in two ways, depending on how it is positioned relative to shading device **13**: [0093] a. It can be positioned on the inward-facing-side of shading device **13** to sense the daylight admitted by shading device **13**, thereby enabling closed-loop daylight control. [0094] b. It can be positioned on the outward-facing side of shading device **13**, thereby enabling open-loop daylight control.

[0095] In the former case, the daylight signal produced by means **11** depends indirectly on the external daylight illuminance (as modulated by shading device **13**), while in the latter case the daylight signal produced by means **11** depends directly on the external daylight illuminance (in the case of a visible-wavelength electro-optical sensor) or indirectly on the external illuminance (in the case of a non-visible-wavelength or temperature sensor).

7.2 Controller **12**

[0096] Controller **12** is a conventional device that implements a control algorithm to regulate the daylight admitted by shading device **13**. It includes a processor executing software steps (and which will typically also perform other tasks in addition to responsive daylight control).

[0097] When performing responsive daylight control, controller **12** accepts the daylight signal from daylight-sensing means **11**, processes it according to the control algorithm, and therefrom produces a control signal to actuate shading device **13**.

[0098] Controller **12** will operate in one of two operating states when performing responsive daylight control (in addition to other conventional states, such as a system power-up state): [0099] a. In an inter-adjustment state, which is the default state while the system is performing responsive daylight control, the controller will periodically evaluate the need for a shading adjustment. If an adjustment is needed, the controller will issue a command to shading device **13** to initiate a shading adjustment, at which point the system will enter an intra-adjustment state. [0100] b. In the intra-adjustment state, the system will attempt to adjust the shading to a setting calculated to result in the desired level of admitted daylight (for open-loop control), or until the daylight signal corresponds to the desired level of admitted daylight (for closed-loop control). After the adjustment is complete, the system will re-enter the inter-adjustment state.

[0101] The system's behavior in the intra-adjustment state is incidental to the subject invention, while its behavior in the inter-adjustment state is what determines its responsiveness to changing daylight levels and is the focus of the subject invention.

7.2.1 FIG. **2**: High-Level Flowchart of Inter-Adjustment State

[0102] FIG. **2** shows a flowchart of the inter-adjustment state of the control algorithm executed by controller **12**. At this high level, the flowchart shown in FIG. **1** is also representative of the inter-adjustments steps performed by conventional responsive-daylight-control systems.

[0103] The operations performed in the inter-adjustment state include a loop over five steps: [0104] a. In a pause step **21**, loop execution is paused for an interval that determines the loop frequency. [0105] b. In an estimation step **22**, the daylight level admitted by shading device **13** is estimated on the basis of the daylight signal from daylight sensing means **11**. If the system is performing closed-loop control, then the daylight signal already represents the admitted daylight. However, if the system is performing open-loop control, then the daylight signal represents the daylight on the outward-facing side of the shading device. In that case, the system estimates the admitted daylight level as a function of the daylight signal and the shading setting of shading device **13** (and optionally other variables), according to an assumed transfer function. [0106] c. In a calculation step **23**, the system subtracts a daylight set-point (representing the desired level of admitted daylight) from the estimate of the admitted daylight obtained in step **22** to obtain an error signal. The error signal is positive when the admitted daylight is greater than the set-point, and negative if the admitted daylight is less than the set-point. [0107] d. In a decision step **24**, the system decides whether a shading adjustment is needed. At least two criteria must be met for the system to decide that a shading adjustment is needed: the error signal obtained in step **23** must fall outside a predetermined range (i.e. a deadband), and shading device **13** must not already be at the limit of its adjustment range in the intended direction. Optionally, the system can also require that additional criteria be met before deciding that a shading adjustment is needed. [0108] e. If in step **24** the system decides that no shading adjustment is needed, pause step **21** is repeated. Otherwise, in a command step **25**, a shading adjustment command is issued to shading device **13**. If the error signal is positive, a “close” command is issued to cause the shading to increase in order to decrease the admitted daylight; if the error signal is negative, an “open” command is issued to cause the shading to decrease in order to increase the admitted daylight. [0109] f. After command step **25**, the system enters the intra-adjustment state until the shading adjustment is completed, after which the system re-enters the inter-adjustment state via pause step **21**.

[0110] As noted above, the pause interval implemented in pause step **21** determines the loop execution frequency and, thus, the system's maximum bandwidth and minimum response time.

7.2.2 Intra-Adjustment State

[0111] The operation of system **10** in the intra-adjustment state is conventional and incidental to the subject invention. However, the following description is provided for the sake of completeness.

[0112] In the intra-adjustment state, controller **12** executes the same steps of FIG. **2** with three modifications: [0113] a. The pause interval of step **21** is set to zero so that the control loop executes more frequently. [0114] b. Decision step **24** evaluates criteria to stop the ongoing shading adjustment (rather than to start an adjustment). Specifically, in decision step **24**, a decision to stop the ongoing shading adjustment is made if either (1) the error signal calculated in step **23** has dropped to an acceptably low value (e.g. zero), or (2) if shading device **13** has reached the limit of its adjustment range. [0115] c. In command step **25**, a command is issued to stop (rather than start) the shading adjustment.

7.3 Electronically-Actuated Shading Device **13**

[0116] Electronically-actuated shading device **13** is a conventional device that provides variable shading in response to commands from controller **12**. Specifically, shading device **13** provides an increase in shading (to reduce admitted daylight) upon receipt of a “close” command from controller **12**, a decrease in shading (to increase the admitted daylight) upon receipt of an “open” command from controller **12**, and cessation of an ongoing shading adjustment upon receipt of a “stop” command from controller **12**. A wide variety of shading devices can be used as shading device **13**, including Smart Windows and motorized window coverings such as curtains, blinds, and shades.

[0117] Ideally, shading device **13** would be a Smart Window with no moving parts and with a continuously-variable visible transmittance which can be instantly adjusted over a wide range. Unfortunately, such Smart Windows are not yet cost-effective for mainstream use, so in the near-term, shading device **13** will most likely be a motorized window covering.

[0118] Among current motorized window coverings, the most advantageous for responsive daylight control is the horizontal blind with motorized slat-tilt function. Such motorized blinds provide relatively unobtrusive, granular daylight control at relatively low cost, and are therefore currently the preferred implementation of shading device **13**.

7.3.1 Convention Regarding Slat Tilt Angles

[0119] A horizontal blind provides minimum shading when its slats are tilted to a near-horizontal angle; the shading increases as the slats are tilted in either direction away from the horizontal. Thus, when shading device **13** is a horizontal blind with a motorized slat-tilt function, “opening the shading” refers to tilting of the slats toward a horizontal angle, while “closing the shading” refers to tilting of the slats in either direction away from the horizontal.

[0120] However, as is well-known in the art, horizontal blinds provide better control of direct sunlight when the slats are tilted so the inside-facing edges are higher than the outside-facing edges. Accordingly, when shading device **13** is a horizontal blind, it will advantageously be operated so that its slats are tilted between a near-horizontal angle (for the “open” position) and a near-vertical angle at which their inside-facing edges are above the outside-facing edges (for the “closed” position).

7.4 Other Aspects of System **10** Incidental to Responsive Daylight Control

[0121] A responsive daylight-control system will typically include other conventional hardware elements, and execute other software operations, in addition to those described above in reference to FIGS. **1** and **2**. Such conventional elements and operations include those associated with implementing a power supply, a user-system interface, an interface to other systems, remote-control functionality, a capability for automatic scheduled shading adjustments, or a system set-up and commissioning process. Such conventional elements and operations are incidental to responsive daylight-control in general (and the subject invention in particular), and are omitted for the sake of clarity.

8 Preferred Embodiments with Asymmetric Response Times

[0122] Referring again to FIGS. **1** and **2**, the response time of system **10** can be defined as the delay between (a) the beginning of a change in the daylight level which will eventually be large enough to require a shading adjustment (per calculation step **23** and decision step **24** of FIG. **2**), and (b) the beginning of the resulting automatic adjustment of shading device **13** of FIG. **1**.

[0123] Since the response time is defined from the beginning of the change in the daylight level, the response time depends on both the characteristics of system **10** and the rate of change of the daylight level. The characteristics of system **10** which determine the response time include: [0124] a. The interval between successive iterations of steps **21** through **24** of FIG. **2**, which is determined by the pause interval implemented in pause step **21**. [0125] b. The criteria for making a shading adjustment evaluated in decision step **24**, and specifically the allowable magnitude of the error signal calculated in calculation step **23** before a shading adjustment is initiated (i.e. the system deadband). [0126] c. Any low-pass filtering or delays implemented in any of the steps of FIG. **2** (as will be discussed subsequently).

[0127] Thus, the minimum response time of system **10** is determined by the pause interval implemented in pause step **21** of FIG. **2**. As previously noted, the maximum acceptable response time in blocking severe daylight glare is only a few seconds, so the pause interval implemented in pause step **21** should ideally be no longer than a few seconds. However, absent other measures that will be subsequently described, a response time of only a few seconds will result in excessively frequent shading adjustments.

[0128] A conventional approach to mitigating this problem is to sacrifice responsiveness by increasing the response time by increasing the pause interval. For example, Lee et al refer to this pause interval as the “activation interval”, and cite a default value of 30 seconds in order to limit distracting operation.

[0129] However, testing of the subject invention confirms that a response time of 30 seconds results in an unacceptably slow response to daylight glare, and yet still does not sufficiently decrease the frequency of shading adjustments in fluctuating daylight levels.

[0130] To overcome this, certain embodiments of the subject invention implement two different response times: one for opening the shading, and one for closing the shading. Such an asymmetric response time can implemented in at least several ways: [0131] a. Filtering can be implemented in the daylight signal chain such that a falling daylight level experiences a longer delay than a rising daylight level. [0132] b. The logic used to actuate shading device **13** can be modified so that the criteria for making a shading adjustment must be met for a certain minimum interval before the adjustment is made, such that the criteria for opening the shading must be met for a longer interval than the criteria for closing the shading. [0133] c. The logic used to actuate shading device **13** can be modified so that a certain minimum interval must elapse between successive shading adjustments in the same direction, such that the minimum interval between shade-opening adjustments is longer than the minimum interval between shade-closing adjustments. [0134] d. An asymmetric deadband can be used, such that the magnitude of the error (i.e. the difference between the estimated and actual daylight levels) must be greater to trigger a shade-opening adjustment than to trigger a shade-closing adjustment.

8.1 Preferred Embodiment with Asymmetric Response Time Implemented in Daylight Signal Chain

[0135] An asymmetric response time can be achieved by inserting a dual-time-constant low-pass filter in the daylight signal chain. Referring again to FIG. **1**, if daylight-sensing means **11** were an analog device, this could be implemented as an analog filter, with separate time-constants for rising and falling signal levels, inserted between sensing means **11** and controller **12**.

[0136] However, in the preferred embodiment, daylight-sensing means **11** has a digital output, and the dual-time-constant low-pass filter is most advantageously implemented via software operations between pause step **21** and decision step **24** of FIG. **2**.

8.1.1 FIG. **3**: Flowchart of Dual-Time-Constant Filter

[0137] FIG. **3** shows a flowchart of such a dual-time-constant low-pass filter **30**. Filter **30** has an input and output, and includes the following: [0138] a. In a decision step **31**, operation branches depending on the sign of the change in the input. The sign of the change is determined by storing the input signal level between loop executions and subtracting the current level from the previous level. [0139] b. If decision step **31** determines that the input signal has increased, operation branches to an optional low-pass filtering step **32** which applies a low-pass filter LPF **1** to the input signal. This is conveniently implemented as a conventional Exponentially-Weighted Moving Average (EWMA), in which the filter output is equal to a weighted sum of the current and previous input values. Because LPF **1** is optional (as described below), it can be omitted, in which case, step **32** can simply pass the input signal unchanged. [0140] c. However, if decision step **31** determines that the input signal has decreased, operation branches to a low-pass filtering step **33** which apples a low-pass filter LPF **2** to the input signal. This is also conveniently implemented as an EWMA. [0141] d. The output of filter **30** is then the sum of the outputs of steps **32** and **33**.

[0142] The time-constant of LPF **2** of step **33** is chosen to be longer than that of optional LPF **1** of step **32**, so that falling daylight levels are smoothed more (and thereby delayed more) than are rising daylight levels. A time-constant of, e.g., a few seconds is appropriate for LPF **1**, while a time-constant of, e.g., a few minutes or longer is appropriate for LPF **2**.

[0143] LPF **1** may not be necessary unless the pause interval in pause step **21** of FIG. **2** is much shorter than a few seconds. This might be the case if a high loop frequency is desired to sense the presence of high-frequency daylight fluctuations (as is the case with other embodiments described herein). Otherwise, the pause interval in step **21** of FIG. **2** can be set to the desired response time for rising daylight levels (e.g. a few seconds), and LPF **1** can be omitted.

[0144] Referring again to FIG. **2**, the steps associated with filter **30** can be inserted in the signal chain anywhere between pause step **21** and decision step **24**. For example: [0145] a. The steps can be inserted between pause step **21** and estimation step **22**, in which case the input of filter **30** is the signal from daylight-sensing means **11** of FIG. **1**, and the output of filter **30** is a filtered (and hence delayed) version of that signal. [0146] b. The steps can be inserted between estimation step **22** and calculation step **23**, in which case the input of filter **30** is the daylight level estimated in step **22**, and the output of filter **30** is a filtered (and hence delayed) version of the estimated daylight level. [0147] c. The steps can be inserted between calculation step **23** and decision step **24**, in which case the input of filter **30** is the error in step **23**, and the output of filter **30** is a filtered (and hence delayed) version of the error.

8.1.2 FIG. **4**: Flowchart of Daylight-Estimation Step with Dual-Time-Constant Filter

[0148] In an exemplar preferred embodiment, the steps to implement dual-time-constant filter **30** are performed in a daylight estimation step **22**B, shown in FIG. **4**, which is performed in lieu of estimation step **22** of FIG. **2**. The dual-time-constant low-pass filtering is thus applied before daylight estimation, so that the system effectively operates on the basis of the filtered (vice actual) daylight level.

8.2 FIG. **5**: Preferred Embodiment with Asymmetric Response Time Implemented in Shading-Control Logic

[0149] Instead of dual-time-constant low-pass filtering in the signal chain (per dual-time-constant filter **30** of FIG. **3**), an asymmetric response time according to the subject invention can

alternatively be implemented in the control logic used to make shading adjustments.
[0150] FIG. **5** shows how this can be implemented as software steps which are performed between decision steps **24** and command steps **25** of FIG. **2**.
[0151] These steps begin with a decision step **41** in which operation branches depending on whether the decision made in step **24** was to increase (close) or decrease (open) the shading: [0152] a. If the decision was to close the shading, operation branches to an optional decision step **42**. Decision step **42** branches to pause step **21** of FIG. **2** unless an interval of at least T**1** has elapsed since the previous shade-opening adjustment. In that case, operation branches to command step **25** of FIG. **2** to issue a command to begin closing the shading. Thus, shade-closing is delayed by T**1** following any shade-opening adjustment, but thereafter multiple shade-closing adjustments can be made consecutively without incurring the delay. [0153] b. If the decision was to open the shading, operation branches to a decision step **43**. Decision step **43** branches to pause step **21** of FIG. **2** unless an interval of at least T**2** has elapsed since the previous shade-closing adjustment. In that case, operation branches to command step **25** of FIG. **2** to issue a command to begin opening the shading. Thus, shade-opening is delayed by T**2** following any shade-closing adjustment, but thereafter multiple shade-opening adjustments can be made consecutively without incurring the delay.
[0154] Interval T**2** of step **43** is chosen to be longer than interval T**1** of step **42**, so there is a longer delay in opening the shading after a shade-closing adjustment than in closing the shading after a shade-opening adjustment. An interval of the order of a few seconds is appropriate for T**1**, while an interval of the order of a few minutes is appropriate for T**2**.
[0155] Optional decision step **42** is necessary only if the pause interval in pause step **21** of FIG. **2** is shorter than a few seconds. This might be the case if a high loop frequency is desired to sense the presence of high-frequency daylight fluctuations. Otherwise, the pause interval in step **21** of FIG. **2** can be set to the desired response time for closing the shading (e.g. a few seconds) and interval T**1** can be made equal to zero, such that step **42** can be omitted.
[0156] Thus, when the steps of FIG. **4** are implemented in addition to the steps of FIG. **2**, system **10** of FIG. **1** has an asymmetric response time with a longer response time in opening the shading (in response to dropping daylight levels) than to closing the shading (in response to rising daylight levels).
[0157] Note that the response times due to intervals T**1** and T**2** apply only to reversals in the direction of shading adjustment. Specifically, interval T**1** applies only to the first shade-closing adjustment after a shade-opening adjustment, while interval T**2** applies only to the first shade-opening adjustment after a shade-closing adjustment; no delay is required between subsequent adjustments in the same direction.
[0158] When compared to the dual-time-constant filter **30** of FIGS. **3** and **4** (in which the response time applies to every shading adjustment), the implementation of FIG. **5** reduces the frequency of shading adjustments while increasing the average magnitude of the adjustments. Many building occupants prefer this behavior.
[0159] If this is not the case, the implementation shown in FIG. **5** can be modified to impose delays on every shading adjustment, as follows: [0160] a. In decision step **42**, the criterion to proceed to step **25** is changed from “ELAPSED TIME SINCE LAST OPEN≥T**1**?” to “ELAPSED TIME SINCE LAST SHADING ADJUSTMENT≥T**1**?” [0161] b. In decision step **43**, the criterion to proceed to step **25** is changed from “ELAPSED TIME SINCE LAST CLOSE≥T**2**?” to “ELAPSED TIME SINCE LAST SHADING ADJUSTMENT≥T**2**?”
[0162] This modification results in behavior similar to that provided by dual-time-constant filter **30** of FIGS. **3** and **4**.
8.3 Preferred Embodiment with Asymmetric Response Time Implemented Via Asymmetric Deadband
[0163] As previously described in reference to FIG. **2**, system **10** makes a shading adjustment only

if decision step **24** determines that the error signal calculated in calculation step **23** falls outside a predetermined range (i.e. the deadband). The deadband determines the precision of system **10** in controlling the admitted daylight and the system's sensitivity to changes in the daylight level.
[0164] Conventionally, the deadband is chosen to be as large as possible (to minimize the frequency of shading adjustments), while still providing the required precision of daylight control.
[0165] Increasing the deadband will make the system less sensitive to daylight changes while also increasing the response times of system **10** to gradual changes in the daylight level. Further, making the deadband asymmetric will yield a different response time for shade-opening than for shade-closing in response to gradual changes in the daylight level. This can be implemented by including the following logic in decision step **24** of FIG. **2**: [0166] a. If the error signal is greater than a positive Close threshold, software operation branches to command step **25** to close the shading; otherwise, operation branches to pause step **21**. [0167] b. If the error signal is less than a negative Open threshold, software operation branches to command step **25** to open the shading; otherwise, operation branches to pause step **21**.
[0168] If the magnitude of the Open threshold is made greater than that of the Close threshold, the deadband will be asymmetric, and the system will have a longer shade-opening response time than a shade-closing response time for gradual changes in the daylight level. This can reduce the average frequency of shading adjustments without sacrificing responsiveness to increasing daylight levels.
[0169] However, increasing the magnitude of the Open threshold will not significantly increase the shade-opening response time to rapid, high-amplitude decreases in the daylight level.
8.4 Advantages and Limitations of Embodiments with Asymmetric Response Time
[0170] Implementation of an asymmetric response time as previously described enables system **10** of FIG. **1** to respond quickly to block glare while still limiting the peak frequency of shading adjustments. Testing shows that this behavior results in substantially greater occupant satisfaction than just increasing the response time symmetrically per conventional approaches.
[0171] However, the testing also shows that an asymmetric response time per se does have two limitations: [0172] a. The delay in opening the shading is longer than necessary when there is little or no problematic daylight fluctuation. Such a situation can occur, for example, when the solar disc passes behind terrain or buildings: there is no sustained daylight fluctuation, so the shading should ideally be opened quickly. [0173] b. When the fluctuation period is comparable to the sum of the shade-opening and shade-closing response times, the delay in shade-opening can cause the shading to open just as the daylight level begins to rise again, which in turn triggers an almost immediate shade-closing adjustment. This opening-then-immediate-closing behavior is annoying to building occupants, and especially so in sustained fluctuation when such a pattern of opening-then-immediate-closing adjustments can occur every few minutes (depending on the response times). Unfortunately, simply increasing the shade-closing response time is not a viable approach to increasing the interval between the opening and closing adjustments, because the system must remain capable of responding quickly to block glare.
9 Preferred Embodiments which Inhibit Shade-Opening Adjustments in Daylight Fluctuation
[0174] Another way of implementing an asymmetric response time is to inhibit shade-opening adjustments during problematic fluctuation while still performing shade-closing adjustments. This effectively increases the shade-opening response time to equal the duration of the problematic fluctuation, but only during the problematic fluctuation.
[0175] This requires a means of detecting or inferring problematic daylight fluctuation, and either: [0176] a. a means of directly suspending adjustments to reduce the shading when problematic fluctuation is detected, or [0177] b. a means of indirectly suspending adjustments to reduce the shading by making shading adjustments on the basis of the maximum (and not instantaneous) value of the daylight level during problematic fluctuation.
[0178] Both approaches have proven equally advantageous from a performance standpoint, but one

may be simpler to implement than the other depending on how other aspects of system **10** are implemented.

[0179] To facilitate a complete understanding of this aspect of the subject invention, the following description includes three sections: [0180] a. a description of a preferred embodiment which indirectly suspends shade-opening adjustments in problematic daylight fluctuation; [0181] b. a description of a preferred embodiment which directly suspends shade-opening adjustments in problematic daylight fluctuation; and [0182] c. a description of a preferred embodiment (and alternatives thereto) of means for detecting or inferring the presence of problematic daylight fluctuation, for use in the previously-described embodiments.

9.1 FIG. **6**: Preferred Embodiment with Indirect Inhibition of Shade Opening in Daylight Fluctuation

[0183] System **10** of FIG. **1** can be modified to indirectly inhibit shade-opening adjustments during daylight fluctuation by modifying estimation step **22** of FIG. **2** as described below.

[0184] FIG. **6** is a flowchart of such a modified estimation step, an estimation step **22**C. Step **22**C is identical to step **22** of FIG. **2**, except that the daylight estimation is preceded by software operations to implement two functional blocks: a fluctuation detector **50** and a peak detector **60**.

[0185] Fluctuation detector **50** detects problematic patterns of daylight fluctuation, and will be described in detail in a subsequent section of this disclosure. It accepts an input **51** and has an output **52**; it produces a “fluctuation” signal on output **52** when the signal on input **51** meets certain criteria.

[0186] Peak detector **60** has a signal input **61**, a control input **62**, and a signal output **63**. Peak detector **60** includes conventional software operations to: [0187] a. store the maximum value of a signal on signal input **61**, and pass that maximum value to signal output **63**, while a “fluctuation” signal is registered on control input **62**; and [0188] b. pass the signal on signal input **61** unchanged to output **63** while a “fluctuation” signal is not registered on control input **62**.

[0189] Input **51** of fluctuation detector **50** and input **61** of peak detector **60** are interconnected, and both receive the output of daylight sensing means **11** of FIG. **1**. Thus, fluctuations in the daylight signal used for responsive daylight control (i.e. the signal which passes through peak detector **60**) are sensed by fluctuation detector **50**.

[0190] Output **52** of fluctuation detector **50** is connected to control input **62** of peak detector **60**, so that the “fluctuation” signal produced by the former determines whether the latter passes the peak value or the unchanged value of the daylight signal to signal output **63**.

[0191] Thus, when estimation step **22** of FIG. **2** is replaced by estimation step **22**C of FIG. **6**, system **10** of FIG. **1** adjusts shading device **13** on the basis of the sensed daylight level when there is no daylight fluctuation, but on the basis of the peak of the sensed daylight level during daylight fluctuation. In this way, the system is able to respond quickly to rising daylight levels, while at the same time avoiding excessively frequent shading adjustments during daylight fluctuation.

9.1.1 Alternative Embodiments with Indirect Inhibition of Shade Opening in Daylight Fluctuation

[0192] In the embodiment described above (and as shown in FIG. **6**), fluctuation detector **50** and peak detector **60** are implemented in estimation step **22**C, which is performed in lieu of step **22** of FIG. **2**. However, peak detector **60** could instead be incorporated in calculation step **23**, or in fact at any point in the signal chain before decision step **24**.

[0193] Also, while FIG. **6** shows that the inputs of both fluctuation detector **50** and peak detector **51** are connected to the output of daylight sensing means **11** of FIG. **1**, the inputs need not be the same. For example, input **51** of fluctuation detector **50** could remain connected to the output of daylight-sensing means **11**, while input **61** of peak detector **60** could instead be driven by the error signal produced in calculation step **23** of FIG. **2**. The only requirement is that input **51** of fluctuation detector **50** must be connected upstream of any fluctuation suppression (e.g. as provided by peak detector **60** or any low-pass filtering in the signal chain).

9.2 FIG. **7**: Preferred Embodiment with Direct Inhibition of Shade Opening in Daylight Fluctuation

[0194] Instead of inhibiting decreases in the sensed daylight level (and thereby indirectly inhibiting shade opening), the fluctuation signal produced by fluctuation detector **50** can instead be used to directly inhibit shade-opening adjustments. This can be done by adding a test for the presence of the "fluctuation" signal produced by detector **50** to the criteria for shade opening in decision step **24** of FIG. **2**.

[0195] FIG. **7** shows such a decision step **24**B which, when performed in lieu of decision step **24** of FIG. **2**, will directly inhibit adjustments to open the shading when the "fluctuation" signal is asserted. As with the embodiment described in reference to FIG. **6**, in this embodiment, fluctuation detector **50** is implemented via software operations performed by controller **12** of FIG. **1**, and will be described in detail subsequently.

[0196] Decision step **24**B includes the following steps: [0197] a. A decision step **71** determines whether the error signal produced by calculation step **23** of FIG. **2** meets criteria to close or open the shading. If decision step **71** determines that the magnitude of the error signal is small enough that no shading adjustment is needed, operation branches to pause step **21** of FIG. **2**. [0198] b. If decision step **71** determines that the error signal is high enough to warrant closing the shading, then operation branches to command step **25**, which issues a command to close the shading. [0199] c. On the other hand, if decision step **71** determines that the error signal is low enough to warrant opening the shading, then operation branches to a decision step **72**. [0200] d. Decision step **72** checks for the presence of fluctuation by checking whether the "fluctuation" signal is being asserted by fluctuation detector **50** (not shown in FIG. **7**). If there is fluctuation, operation branches to pause step **21** of FIG. **2**. [0201] e. On the other hand, if decision step **72** determines that there is no fluctuation, then operation branches to command step **25**, which issues a command to open the shading.

[0202] Thus, when system **10** of FIG. **1** implements decision step **24**B of FIG. **7** instead of decision step **24** of FIG. **2**, it will inhibit shade-opening adjustments in the presence of daylight fluctuation, but will open the shading normally when there is no daylight fluctuation.

9.3 Fluctuation Detector **50**

[0203] The purpose of fluctuation detector **50** is to detect the current or imminent presence of problematic fluctuation as reliably and as quickly as practicable.

9.3.1 Problematic Fluctuation Versus Non-Problematic Fluctuation

[0204] As previously stated, the primary cause of occupant annoyance with responsive daylight control is a pattern of shading adjustments in which the interval between opposing adjustments is less than a few minutes (and sometimes less than ten minutes or more, depending on the occupant). Fluctuation which would tend to cause such a pattern of shading adjustments is considered herein to be problematic fluctuation. Problematic fluctuation appears to be caused solely by intermittent shading of the solar disc by moving clouds.

[0205] Conversely, fluctuation which can be compensated without such a pattern of frequent shading adjustments in opposite directions is considered herein to be non-problematic fluctuation. Non-problematic fluctuation is characterized by gradual changes in the daylight level over periods of at least ten minutes (e.g. due to changes in the solar angle of incidence caused by the earth's rotation), as well as to infrequent isolated changes in the daylight level over periods as short as a few seconds (e.g. due to obscuration of the solar disc by terrain or buildings, again caused by the earth's rotation).

9.3.2 Approaches for Detecting Problematic Fluctuation

[0206] Since problematic fluctuation appears to be caused by moving clouds, it can be detected indirectly via weather information. Alternatively, it can be detected directly via fluctuations in the daylight irradiance, on the basis of the distinguishing characteristics described briefly above (and in more detail below). Fluctuation detector **50** can exploit either approach.

[0207] However, direct detection via irradiance fluctuation is generally less expensive and easier to implement in systems that do not already have a means of obtaining weather information, particularly because a responsive daylight-control system will necessarily already include a means of sensing daylight irradiance (e.g. sensing means **11** of FIG. **1**). Accordingly, the following description of fluctuation detector **50** begins with embodiments which use direct detection.

9.3.3 Direct Detection of Problematic Fluctuation

[0208] A practical way of distinguishing problematic fluctuation from non-problematic fluctuation is via characteristics of the fluctuation spectrum, i.e. the frequency content of the fluctuation (e.g. as represented by the amplitude-spectral-density, power-spectral-density, or energy-spectral-density of a signal representing the fluctuation).

[0209] However, the frequency ranges associated with problematic and non-problematic fluctuation are subjective (inasmuch as they depend on occupants' reaction to frequent shading adjustments), and are therefore best expressed in terms of approximate order-of-magnitude frequency bounds. Testing associated with the subject invention indicates that non-problematic fluctuation appears to be concentrated at frequencies lower than approximately 1E-3 Hz (corresponding to a fluctuation period of 17 minutes) when caused by the gradually changing solar angle-of-incidence, or at frequencies higher than approximately 1E-1 Hz (corresponding to a fluctuation period of 10 seconds) when caused by obscuration of the moving solar disc by terrain or buildings. Conversely, substantial spectral content between those approximate frequencies represents problematic fluctuation caused by moving clouds.

9.3.3.1 Spectral Characteristics of Fluctuation Due to Moving Clouds

[0210] Because irradiance fluctuation has significant implications for the planning and design of solar power installations, the moving-cloud fluctuation spectrum has been studied extensively in the field of solar energy; see, for example Anvari et al (2016) and Olama et al (2020).

[0211] This research indicates three facts about the spectrum of fluctuation due to moving clouds:

[0212] a. The moving-cloud fluctuation spectrum is broader than the above-defined spectrum of problematic fluctuation; the moving-cloud fluctuation spectrum ranges from approximately 1E-4 Hz to 1 Hz. [0213] b. When observed over at least several days, the moving-cloud fluctuation spectrum has the shape of a Kolmogorov turbulence spectrum, in which the Power-Spectral Density (PSD) is proportional to a power (exponent) of the frequency. The portion of this spectrum which represents problematic fluctuation (i.e. frequencies between approximately 1E-3 to 1E-1 Hz) appears to be within the so-called Kolmogorov inertial range, in which the power-law exponent is equal to approximately −5/3. Above 1E-1 Hz the shape is consistent with the Kolmogorov dissipative range, in which the negative exponent has a larger magnitude (i.e. the PSD begins to fall off more steeply with increasing frequency). [0214] c. However, the moving-cloud fluctuation spectrum cannot be assumed to adhere closely to this Kolmogorov shape when observed over intervals shorter than several days. The shape of the short-term spectrum changes with time, so that a spectrogram (frequency-versus-time plot) is necessary to fully characterize the short-term fluctuation due to moving clouds.

[0215] Nevertheless, testing associated with the subject invention suggests that the short-term spectrum of fluctuation due to moving clouds does resemble a Kolmogorov spectrum sufficiently well to facilitate discrimination between problematic and non-problematic fluctuation. This fact is exploited by the subject invention.

9.3.3.2 Fluctuation Detection Based on Spectral Discrimination

[0216] Assuming that problematic fluctuation is caused only by moving clouds, and under conditions when the assumption of a Kolmogorov spectrum for moving-cloud fluctuation is valid, the presence of problematic fluctuation can be reliably inferred on the basis of the Power Spectral Density (PSD) in an irradiance signal at any frequency between approximately 1E-3 and 1E-1 Hz. Since the minimum time needed to sense the PSD at a given frequency is approximately equal to the reciprocal of that frequency, the fluctuation detection can be made in approximately 10 seconds at 1E-1 Hz, but would take 1000 seconds at 1E-3 Hz. The former is ostensibly preferable since it is desirable to make the fluctuation detection as quickly as possible.

[0217] On the other hand, because the short-term fluctuation spectrum does not necessarily resemble a Kolmogorov turbulence spectrum at every instant in time, the absence of a significant PSD at 1E-1 Hz over a 10-second observation interval does not guarantee the absence of problematic fluctuation at lower frequencies. For example, there can be repeated short intervals of high PSD at 1E-1 Hz, interspersed with several minutes of low PSD at 1E-1 Hz. Then, if the fluctuation detection is based solely on the PSD at 1E-1 Hz, the fluctuation detector will issue the “fluctuation” signal intermittently every few minutes. This, in turn, would cause system **10** (when performing the steps of FIGS. **6** and **7**) to make shade-opening adjustments at the excessively frequent rate of every few minutes.
[0218] Thus, there is a trade between the reliability of the fluctuation detection and the interval over which the detection is made. This is discussed further in the context of the exemplar embodiments described below.
9.3.4 FIG. **8**: Fluctuation Detector **50** Using Broadband Amplitude Demodulation
[0219] Problematic fluctuation can be distinguished from non-problematic fluctuation on the basis of the fluctuation amplitude averaged over an interval, which in turn can be sensed with a broadband amplitude demodulator driven from a signal representing the daylight level. The amplitude of the broadband fluctuation will also include a component due to high-frequency non-problematic fluctuation, but because non-problematic fluctuation is short-lived, it will have relatively little power over the averaging interval.
[0220] FIG. **8** shows a flowchart of fluctuation detector **50** implemented using such an approach. While it could be implemented in hardware (in which case the flowchart of FIG. **8** can be interpreted as a hardware block diagram), it is preferably implemented via software operating steps executed by controller **12** of FIG. **1**.
[0221] Detector **50** includes software operations to perform five conventional processing steps:
[0222] a. A conventional differentiator block **53** performs differentiation with respect to time of the signal on input **51** in order to pass (and optionally amplify) only the time-varying component thereof. The output of block **53** is positive for increases in the signal on input **51** and negative for decreases thereof, with the magnitude depending on the rate of increase or decrease (and the amount of amplification, if any). If input **51** were an analog input, block **53** could consist of a capacitor or an active differentiator; in the preferred embodiment, it consists of a software step to subtract the previous value of the signal on input **51** from the current value (with optional multiplication to provide gain). [0223] b. A conventional rectifier block **54** performs full-wave rectification of the output of block **53**, passing (and optionally amplifying) the magnitude of the latter output. If block **54** were implemented in analog hardware, it could consist of an active rectifier; in the preferred embodiment, block **54** is implemented as an absolute-value function (with optional multiplication) in a software step. Alternatively, with some increase in complexity, rectifier block **54** could be replaced by a conventional power-law detector to respond to the power, rather than rectified amplitude, of the output of differentiator block **53**. [0224] c. A conventional averager block **55** averages the output of rectifier block **54** over an averaging interval. If implemented in analog hardware, block **55** could consist of a low-pass filter. In the preferred embodiment, block **55** consists of software steps to implement a conventional moving-average filter over the desired averaging interval. [0225] d. A conventional comparator block **56** asserts the “fluctuation” signal when the output of averager block **55** exceeds a threshold, and de-asserts the “fluctuation” signal when the output of averager block **55** drops below a threshold. If implemented in analog hardware, block **56** could be implemented as an analog comparator; in the preferred embodiment, it is implemented as software operations performing a conditional test. [0226] e. An optional conventional pulse-stretcher block **57** produces an output pulse of at least a predetermined duration (i.e. the pulse interval) on an output **52** when triggered by an input. Pulse-stretcher block **57** is retriggerable, so that multiple triggers within the pulse interval result in a single continuous pulse on output **52**. Thus, because pulse-stretcher block **57** is driven by the output of comparator

block **56**, it extends the duration of any “fluctuation” signal asserted by comparator block **56** to at least the pulse interval. If implemented in hardware, pulse-stretcher block **57** could be implemented as a conventional retriggerable monostable multivibrator, but in the preferred embodiment is implemented via software operations to provide the same functionality.

[0227] Differentiator block **53** acts as a high-pass filter, with maximum sensitivity at a frequency that corresponds to the sampling rate at the input of fluctuation detector **50** (which is determined by the pause interval in pause step **21** of FIG. **2**). If the pause interval is short enough to enable system **10** to respond quickly to glare-inducing conditions (e.g. 1 second), then the frequency at which differentiator block **53** has maximum sensitivity will approach 1 Hz.

[0228] However, as previously described, problematic fluctuation is limited to frequencies between approximately 1E-3 and 1E-1 Hz, while non-problematic fluctuation can have significant power at frequencies as high as 1 Hz. The purpose of averager block **55** is to attenuate the effects of the high-frequency non-problematic fluctuation, which are short-lived isolated events and hence get averaged-out over the averaging interval.

[0229] Averager block **55** also determines the response time of fluctuation detector **50** to the onset of fluctuation: the longer the averaging interval window size (i.e. the product of the sampling rate and the number of samples in the moving-average), the longer the response time. Thus, the averaging interval represents a trade-off. If the averaging interval is too long, system **10** will make an excessive number of opposing shading adjustments before fluctuation detector **50** is able to assert the “fluctuation” signal. On the other hand, if the averaging interval is too short, then short-lived non-problematic fluctuation will not be sufficiently attenuated, resulting in an excessive rate of false positive assertions of the “fluctuation” signal.

[0230] The appropriate averaging interval will depend, in part, on the shade-opening response time implemented by system **10**. Specifically, if the shade-opening response time is not deliberately increased (e.g. as previously described in reference to FIGS. **3**, **4**, and **5**), then a relatively short averaging interval (e.g. less than 100 seconds, and perhaps as short as 10 seconds) appears necessary to limit the frequency of shading adjustments at the onset of problematic fluctuation.

[0231] As previously described, problematic fluctuation will not necessarily have a Kolmogorov spectrum over any given averaging interval. Specifically, there can be repeated intervals of high-frequency fluctuation (e.g. at 1E-1 Hz) interspersed with intervals of minute or two without fluctuation. Under these conditions, fluctuation detector **50** should ideally produce a continuous “fluctuation” signal. However, if the averaging interval is relatively short (e.g. only 10 seconds), comparator block **56** will issue the “fluctuation” signal intermittently every minute or two, which can cause system **10** to make excessively frequent shading adjustments. This is mitigated by optional pulse-stretcher block **57**, which lengthens the duration of any “fluctuation” signal produced by comparator block **56** to at least the pulse interval. Since pulse-stretcher block **57** is retriggerable, the fluctuation signal will be asserted continuously when the pulse duration is equal to or greater than the interval between fluctuations.

[0232] The pulse duration is a trade-off: if it is too short, then the “fluctuation” signal might not be continuously asserted during sustained fluctuation, but if it is too long, then shade-opening adjustments will be unnecessarily delayed after the cessation of problematic fluctuation.

[0233] The averaging interval and pulse-stretcher pulse duration can be optimized empirically according to the information provided herein.

9.3.4.1 Modifications to Fluctuation Detector **50** for Use with Closed-Loop Irradiance Sensor

[0234] As described in reference to FIG. **6**, input **51** of fluctuation detector **50** can be the same irradiance signal used as the basis for daylight control, i.e. it can be the output of daylight sensing means **11**. Also, as described in reference to FIG. **1**, sensing means **11** can be disposed to sense daylight admitted by shading device **13** to enable closed-loop daylight control.

[0235] In such a configuration, the irradiance signal on input **51** of fluctuation detector **50** will vary not only with changes in the outside daylight irradiance, but also with changes in the setting of the shading device. To prevent the latter changes from being incorrectly detected as daylight fluctuation, the software operations associated with differentiator block **53** should be suspended in the intra-adjustment state of system **10**, i.e. during shading adjustments.

9.3.5 Alternative Implementations of Fluctuation Detector **50**

[0236] Feasible implementations of a fluctuation detector according to the subject invention can span a range of performance and complexity. Detector **50** as described in reference to FIG. **8** is optimized for simplicity, and improved performance may be possible via more complex implementations, some of which are described below.

9.3.5.1 Fluctuation Detector with Tailored Frequency Response

[0237] Differentiator block **53** of FIG. **8** acts a high-pass filter whose sensitivity increases by 20 dB per decade with increasing frequency. On the other hand, problematic fluctuation (assuming a Kolmogorov spectrum) has a PSD which decreases by approximately 17 dB per decade with increasing frequency.

[0238] Further, assuming that pause interval in step **21** of FIG. **2** is short enough to enable system **10** to respond quickly to glare-inducing conditions, the output of differentiator block **53** will peak at a frequency at which the PSD of non-problematic fluctuation is greater than that of problematic fluctuation (e.g. 1 Hz).

[0239] Therefore, the performance of fluctuation detector **50** can be improved by replacing differentiator block **53** with a conventional filter which passes only frequencies lower than those of non-problematic fluctuation, but also blocks the DC (non-varying) component of the signal on input **51**. Such a filter is thus a bandpass filter.

[0240] As previously stated, the spectrum of problematic fluctuation ranges from approximately 1E-3 to 1E-1 Hz, so a bandpass filter which spans this range (or a subset thereof) can be used for the detection. However, the lower-frequency limit of the passband represents a trade between the reliability of detecting problematic fluctuation and the time required to make the detection: [0241] a. Detection reliability can be maximized with a filter response that exactly matches the expected fluctuation spectrum, i.e. a passband of 1E-3 Hz to 1E-1 Hz and a response that drops by 17 dB per decade with increasing frequency (consistent with the assumption of a Kolmogorov spectrum). However, since the fluctuation period at 1E-3 Hz is 17 minutes, taking full advantage of such a wide passband would result in an unacceptably long detection time. [0242] b. The detection time can be reduced by raising the lower-frequency limit of the passband to something greater than 1E-3 Hz. Unfortunately, this reduces the width of the passband and hence the fluctuation power captured by the filter, which is exacerbated by the 17 dB per decade loss in PSD with increasing frequency (assuming a Kolmogorov fluctuation spectrum). The result is a significant decrease in the reliability of the fluctuation detection. However, testing indicates that high reliability can still be achieved with a lower-frequency limit of approximately 1E-2 Hz (i.e. via a decade-wide passband that ranges from 1E-2 Hz to 1E-1 Hz). Assuming a detection time of at least one fluctuation period at the lowest frequency of interest, this would result in a minimum delay of approximately 100 seconds in the issuance (or cessation) of the “fluctuation” signal. [0243] c. It appears possible to narrow the passband still further while maintaining an acceptable reliability of detection. For example, an octave-wide passband extending from 5E-2 Hz to 1E-1 Hz decreases the minimum response time to approximately 20 seconds, while still offering reasonably reliable detection of problematic fluctuation.

[0244] Based on testing to date, it appears that useful embodiments of the subject can be realized with a lower-frequency passband limit between approximately 1E-2 and approximately 5E-2 Hz, with an upper-frequency passband limit of approximately 1E-1 Hz.

[0245] Exemplar approaches for implementing fluctuation detection with a tailored frequency response are described below.

9.3.5.2 FIG. **9**: Fluctuation Detector Using Band-Limited Amplitude Demodulation with a Bandpass Filter

[0246] FIG. **9** shows a flowchart of a fluctuation detector, fluctuation detector **50**B, with a bandpass response. While it is advantageously implemented via software operating steps executed by controller **12** of FIG. **1**, it could also be implemented in hardware, in which case the flowchart of FIG. **9** can be interpreted as a hardware block diagram.

[0247] Detector **50**B is a form of conventional band-limited amplitude demodulator, and includes three elements: [0248] a. A conventional bandpass filter **81** band-limits the signal on input **51** (which, as previously described in reference to detector **50**, will fluctuate in the presence of daylight fluctuation). Bandpass filter **81** has a passband that is chosen according to the previously-described criteria. If the signal on input **51** were an analog signal, filter **81** could be an analog filter, but in the preferred embodiment is a conventional digital filter implemented via software operations executed by controller **12** of FIG. **1**. [0249] b. A conventional detector **82** produces a signal that depends on the amplitude at the output of filter **81**. This can be either in analog form, or (in the preferred embodiment) in the form of software operations executed by controller **12**. [0250] c. Comparator block **56** produces the "fluctuation" output signal when the output of detector **82** exceeds a threshold.

9.3.5.3 FIG. **10**: Fluctuation Detector Using Band-Limited Amplitude Demodulation Via the Goertzel Algorithm

[0251] An advantageous way of implementing bandpass filter **81** and detector **82** of detector **50**B as shown in FIG. **9** is via software operations to implement the Goertzel algorithm. An implementation of a fluctuation detector using such an approach is fluctuation detector **50**C, shown in flowchart form in FIG. **10**, which includes two elements: [0252] a. A Goertzel block **83** includes software operations to implement a Goertzel algorithm. Well-known in the art of digital signal processing, a Goertzel algorithm (of which several variations are known) is a way of efficiently determining the magnitude, and optionally the phase, of a signal in a single frequency band of interest. Only the magnitude (or optionally magnitude squared) is required for detector **50**C, which further simplifies the implementation of the algorithm. In the preferred embodiment, Goertzel block **83** produces only the magnitude squared. [0253] b. The output of Goertzel block **83** feeds comparator block **56**, which produces the "fluctuation" signal on output **52** when its input exceeds a threshold.

[0254] Given the relatively low frequencies of daylight fluctuation, fluctuation detector **50**C can be implemented with even a low-cost microcontroller, and yet provides the same functionality (in this application) as the much more computationally-intensive Discrete Fourier Transform.

9.3.5.4 Multi-Spectral Fluctuation Detection

[0255] As an extension of the bandpass-filtering approaches described above, multiple bandpass filters, each tuned to a different frequency, could be used to sample the fluctuation PSD. These could be implemented via a buffer to store time-sampled daylight levels, along with software operations to transform those time-domain samples into frequency-domain samples via a conventional implementation of a Discrete-Fourier Transform (DFT), Walsh-Hadamard Transform (WHT), or a wavelet-based transform.

[0256] A conventional algorithm could then be used to make the fluctuation detection on the basis of the fluctuation powers in multiple frequency bands. For example, the detection could be made on the basis of the ratio of the power in a lower-frequency spectral band to the power in a higher-frequency spectral band.

9.3.5.5 Fluctuation Detection Via Spectrogram

[0257] Rather than making the detection based just on the power in one or more frequency bands, the detection could be made on the basis of the change in the shape of the spectrum over time, i.e. via a spectrogram of the fluctuation. Such an approach in known, for example, in the fields of speech recognition, and could be particularly advantageous when coupled with Machine Learning (ML) techniques (as described below).

9.3.5.6 Fluctuation Detection Based on Alternative Irradiance Signal

[0258] In the embodiments described above, the irradiance signal used as the input for fluctuation detection is the same signal used as the basis for daylight estimation. For example, in FIGS. **6** and **12**, the input of fluctuation detector **50** is the same signal used as the input for peak detector **60** (FIG. **6**) and dual-time-constant filter **30** (FIG. **12**).

[0259] However, the signal used as the basis for the fluctuation detection need not be the same as that used for daylight estimation.

[0260] For example, if daylight-sensing means **11** is located on the inward-facing side of shading device **13** to enable closed-loop daylight control, then input **51** of fluctuation detector **50** could be connected to the output of an illuminance sensor located on the outward-facing side of shading device **13**. Conversely, if daylight-sensing means **11** is located on the outward-facing side of shading device **13** to enable open-loop daylight control, then input **51** of fluctuation detector **50** could be connected to the output of an illuminance sensor located on the inward-facing side of shading device **13**.

[0261] As another example, input **51** could be connected to the real-time power output signal of the inverter in a building-mounted solar power installation to detect daylight fluctuations on the basis of fluctuations in the photovoltaic power output.

9.3.6 Indirect Detection of Problematic Fluctuation

[0262] As previously stated, problematic fluctuation is due to intermittent shading by moving clouds. It can therefore be detected indirectly via weather information, or by sensing the presence of moving clouds through analysis of imagery from a sky-facing camera.

9.3.6.1 FIG. **11**: Fluctuation Detector Using Weather Api

[0263] Real-time weather data to enable indirect detection of ongoing or imminent fluctuation can be obtained via an Application Programming Interface (API) to any one of several online weather services. FIG. **11** shows a functional block diagram of a fluctuation detector **50**D using such a weather API and consisting of two elements: [0264] a. A weather-service API **84** is a conventional application programming interface and means of connection to an online weather service. [0265] b. A fluctuation-detection algorithm **85** is an algorithm for processing data obtained from API **84** to infer ongoing or imminent fluctuation.

[0266] Both API **84** and algorithm **85** involve software operations which could be executed by controller **12** of FIG. **1**, or could alternatively be performed by another processor. In a preferred embodiment, fluctuation detector **50**D is implemented via software operations executed on a server located remotely from the other elements of system **10** of FIG. **1**. This is advantageous because it allows one instance of fluctuation detector **50**D to serve many instances of system **10** which experience the same weather conditions (e.g. located in the same building or campus).

[0267] A variety of approaches are possible in implementing algorithm **85**: [0268] a. As previously stated, irradiance fluctuation has significant implications for the planning and design of solar power installations, and has therefore been studied extensively in the field of solar energy. Some of these studies have been aimed at predicting the statistics of the spatiotemporal fluctuation of the irradiance in a given geographic area on the basis of historical weather data for that area. [0269] b. For example, Bright et al (2015) have shown that local irradiance fluctuation on a 1-minute scale can be reliably predicted using hourly weather data on cloud cover, surface wind speed, cloud height, and atmospheric pressure. Algorithm **85** could therefore consist of the steps necessary to evaluate the irradiance time-series data produced by the Bright irradiance model (or a similar model) according to the frequency-domain criteria for problematic fluctuation previously defined herein. [0270] c. However, experiments in connection with development of the subject invention indicate that ongoing or imminent fluctuation can be inferred using a simpler model that requires fewer weather data. Specifically, it appears that a useful indication of problematic fluctuation may be possible via a simple function of just the cloud cover and surface wind speed. [0271] d. Alternatively, algorithm **85** could be implemented as a Machine-Learned (ML) model trained to detect ongoing or imminent problematic fluctuation using the same weather variables used by the

Bright model. This would likely yield the most reliable indirection detection of problematic fluctuation, but like all ML approaches would require a significant amount of data to train the model.

[0272] Fluctuation detector **50**D is more complex than embodiments which perform direct detection of problematic fluctuation (such as fluctuation detectors **50**, **50**B, and **50**C), and there are typically costs associated with API access to a standard weather service. However, unlike direct detection, this approach can predict the onset and cessation of problematic fluctuation. Further, the increased complexity and costs associated with access to a weather service can be mitigated by sharing once instance of fluctuation detector **50**D among many proximal instances of system **10**, as previously described.

9.3.6.2 Indirection Detection of Fluctuation Via Imagery from Sky-Facing Camera

[0273] Use of a sky-facing camera to monitor sky conditions (e.g. cloud cover) is well-known in the meteorological sciences. The presence of moving clouds can be detected using conventional image-processing techniques to compare successive image frames produced by such a camera, which could then indirectly indicate the presence of daylight fluctuation.

[0274] However, this approach ostensibly provides little advantage over direct detection of problematic fluctuation, and is also significantly more expensive unless a sky-facing camera is already present.

9.3.7 Fluctuation Detection Based on Multiple Sources of Information

[0275] Increased reliability in detection of problematic fluctuation is likely achievable by basing the fluctuation detection on more than one of the types of information described above. For example, fluctuation detector **50** could subsume the functional blocks of FIG. **8** while also including API **84** to obtain data from an online weather service. In such a system, the “fluctuation” signal could be issued on the basis of the output of comparator block **56** if the data from API **84** indicates partly cloudy conditions, but suppressed if the weather data indicates clear-sky or fully overcast conditions. This would allow system **10** to respond quickly to changes in the daylight level that are not due to problematic fluctuation (e.g. due to obscuration of the solar disc by terrain or buildings).

9.3.8 Fluctuation Detection Via Machine-Learned Model

[0276] As previously stated, an ML model could be advantageously used for indirect detection of problematic fluctuation on the basis of weather data. However, practitioners will appreciate that an ML model could also be used for direct detection of fluctuation, and the inputs to an ML-based fluctuation detector could include any and all of the signals or information described above. For example, an ML-based approach could be used to recognize patterns associated with problematic fluctuation in a spectrogram (frequency versus time plot) of the irradiance.

[0277] An ML-based approach could be particularly advantageous in a supervised-learning context, in which the system includes a user-system interface to allow an occupant to indicate either an excessive or an inadequate adjustment frequency to “teach” the ML model.

9.3.9 Advantages and Disadvantages of Alternative Implementations of Fluctuation Detector **50**

[0278] Some of the alternative implementations of fluctuation detector **50** described above are potentially capable of greater reliability in the detection of problematic fluctuation than is the relatively simple implementation described in reference to FIG. **8**. However, the implementation of FIG. **8** provides sufficiently reliable fluctuation detection for typical applications of system **10**, and will typically be simpler and less expensive to implement than the alternatives. In particular, the software operations needed to implement fluctuation detector **50** as shown in FIG. **8** are within the capabilities of even a simple 8-bit microcontroller.

[0279] However, if a more capable processing device is present for other reasons, or if the associated software operations are off-loaded to a remote (e.g. cloud-based) server, then one of the more sophisticated fluctuation detection approaches described above could be implemented without any additional hardware overhead and would therefore be preferable.

9.4 Advantages and Limitations of Inhibiting Shade Opening in Daylight Fluctuation

[0280] Use of fluctuation detection (e.g. via fluctuation detector **50** of FIG. **8**) to inhibit shade opening (e.g. indirectly by inhibiting decrease in a daylight signal, as shown in FIG. **6**, or directly as shown in FIG. **7**), enables system **10** of FIG. **1** to respond quickly to isolated changes in the daylight level while avoiding distracting reversals of the direction of shading adjustments during problematic fluctuation of the daylight level. Testing shows that this behavior results in substantially greater occupant satisfaction than just increasing the response time symmetrically per conventional approaches.

[0281] However, there is necessarily a delay between the onset of problematic fluctuation and assertion of the "fluctuation" signal, during which time there can be an undesirably high frequency of opposing shading adjustments. There is also a delay between cessation of problematic fluctuation and de-assertion of the "fluctuation" signal, which unnecessarily delays shade opening when there is no risk of glare.

[0282] This delay can be minimized via the previously-described techniques, but this also reduces the reliability of the fluctuation detection (and increases the rate of false "fluctuation" signals when there is no problematic fluctuation). This dilemma can be mitigated by coupling an asymmetric response time (as previously described in reference to FIGS. **3**, **4**, and **5**) with inhibition of shade-opening adjustments in daylight fluctuation.

10 Preferred Embodiments with Asymmetric Response Time and Inhibition of Shade Opening in Daylight Fluctuation

[0283] As described above, an asymmetric response time (e.g. as described in reference to FIGS. **3**, **4**, and **5**) and inhibition of shade opening in daylight fluctuation (e.g. as described in reference to FIGS. **6** and **7**) are each individually advantageous over the prior art, but are also complementary and thus even more advantageous when employed together.

[0284] Specifically, the longer shade-opening response time can be used to limit the shading adjustment frequency during the onset of fluctuation, before the fluctuation detector is able to issue the "fluctuation" signal. This, in turn, allows the use of a shorter shade-opening response time than would be possible without the fluctuation detector, and/or shorter averaging and pulse-stretcher intervals in the fluctuation detector than would be possible without the asymmetric response time. This can maximize responsiveness to non-problematic fluctuation without increasing the risk of distracting operation during problematic fluctuation. Various embodiments of such a system are possible and potentially advantageous.

10.1 FIG. **12**: Preferred Embodiment with Asymmetric Response Time and Indirect Inhibition of Shade Opening in Daylight Fluctuation

[0285] Daylight estimation step **22** of FIG. **2** can be modified to provide system **10** of FIG. **1** with an asymmetric response time in addition to the capability to indirectly inhibit shade-opening adjustments in daylight fluctuation. FIG. **12** shows a flowchart of such a modified estimation step, an estimation step **22**D. It is equivalent to step **22**C of FIG. **6**, except that dual-time-constant filter **30** of FIG. **3** is inserted between the output of daylight sensing means **11** of FIG. **1** and input **61** of peak detector **60**.

[0286] Therefore, the output of step **22**D will represent the daylight level smoothed with an asymmetric response time when there is no daylight fluctuation (as sensed by detector **50**), but will represent the peak daylight level when there is daylight fluctuation. Thus, when system **10** of FIG. **1** performs step **22**D instead of step **22** of FIG. **2**, it will have an asymmetric response time to changes in the daylight level when there is no sustained daylight fluctuation, but will only close (and not open) shading device **13** during daylight fluctuation.

10.2 FIG. **13**: Preferred Embodiment with Asymmetric Response Time and Direct Inhibition of Shade Opening in Daylight Fluctuation

[0287] The software steps of FIG. **2** can be modified to provide system **10** of FIG. **1** with an asymmetric response time in addition to the capability to directly inhibit shade-opening adjustments in daylight fluctuation. FIG. **13** shows how this can be done by inserting previously-described decision steps **41**, **42**, **43**, and **72** between decision step **24** and command step **25** of FIG. **2**: [0288] a. If decision step **24** determines that the criteria for a shading adjustment have been met, then operation branches in step **41** depending on the direction of the required shading adjustment. [0289] b. If the required adjustment is to close the shading, step **42** is performed which checks to ensure that the shade-closing criteria are continuously met for time T**1**. If this is the case, operation proceeds to command step **25** to close the shading; otherwise, operation proceeds to pause step **21** of FIG. **2**. [0290] c. On the other hand, if the required adjustment is to open the shading, operation proceeds from step **41** to step **72**, which checks for the presence of fluctuation by checking whether the "fluctuation" signal is being asserted by fluctuation detector **50** (not shown in FIG. **13**). If there is fluctuation, operation branches to pause step **21** of FIG. **2**; otherwise, operation branches to command step **25**, which issues a command to close the shading.

[0291] Thus, when system **10** of FIG. **1** performs the steps shown in FIG. **13** in addition to those shown in FIG. **2**, it will have an asymmetric response time to changes when there is no sustained daylight fluctuation, but will only close (and not open) shading device **13** during daylight fluctuation.

10.3 Advantages of Asymmetric Response Time with Inhibition of Shade Opening in Daylight Fluctuation

[0292] The combination of an asymmetric response time and inhibition of shade-opening adjustments in daylight fluctuation is more advantageous than each applied individually, at only a small increase in complexity. Specifically, it can provide a shorter response to isolated changes in the daylight level without a significant increase in the frequency of distracting shading adjustments.

11 Preferred Embodiment with Shade-Opening Response Time Adjusted to Maximize Battery Life

[0293] As previously described, the frequency of shading adjustments made by a responsive daylight-control system can be minimized, while still preserving the benefits of responsive daylight control, by increasing the shade-opening response time. In addition to maximizing occupant satisfaction, this can also maximize battery life in battery-powered automated-shading systems. The subject invention can provide the latter benefit in at least three ways: [0294] a. In a system which is capable of being powered by either battery power or mains-supplied power, the shade-opening response time can be automatically selected on the basis of the type of power source. Specifically, a longer shade-opening response time can be selected when under battery power than when under mains power. [0295] b. In a battery-powered system, the shade-opening response time can be automatically selected on the basis of the presence or on/off state of a power-consuming peripheral such as a RF transceiver. Specifically, a longer shade-opening time-constant can be selected if an RF transceiver is present and enabled. [0296] c. In a battery-powered system, the shade-opening response time can be increased with decreases in the remaining battery charge (e.g. as inferred by the battery voltage or a coulomb-counting device).

[0297] All three of the above can be employed simultaneously.

11.1 Preferred Embodiment with Shade-Opening Response Time Based on Power Source

[0298] Embodiments of the subject invention which implement asymmetric response times (such as those previously described in reference to FIGS. **3**, **4**, **5**, **12**, and **13**) can be modified to make the shade-opening response time contingent on the type of power source. This is useful in a responsive daylight-control system which, at the discretion of the user, can be powered by a battery (in which case a relatively long shade-opening response time may be preferable to preserve battery life), or by mains power (in which case a relatively short shade-opening response time may be preferable to maximize responsiveness to falling daylight levels).

11.1.1 FIG. **14**: Block Diagram of Responsive Daylight-Control System with Configurable Power Source

[0299] FIG. **14** shows a block diagram of a responsive daylight-control system **10**B which can be powered by either battery power or mains-derived power. It is similar to system **10** of FIG. **1** except for the addition of a configurable power source **90** and the replacement of controller **12** with a controller **12**B: [0300] a. Configurable power source **90** is a conventional power supply capable of accepting power from either a battery or a mains supply, and providing that power to other elements. In the preferred embodiment, power source **90** includes a battery supply (including a battery holder and battery contacts to secure and accept power from a battery), and a coaxial (barrel) jack to accept DC power from a mains-powered source such as an AC-to-DC converter. Per conventional practice, the battery supply and coaxial power jack are connected in parallel in an electrical OR configuration so that both can supply power to controller **12**B, with a MOS transistor used to isolate the battery supply from the mains-derived DC power. [0301] b. Controller **12**B is similar to controller **12**, except that it includes conventional means of sensing the presence of a battery in source **90**. In the preferred embodiment, this consists of an Analog-to-Digital Converter (ADC) input which senses the voltage on the battery-side of the MOS isolation transistor; a non-zero voltage at this point indicates the presence of a battery. Controller **12**B also includes conventional means of passing power (e.g. a power bus) from source **90** to shading device **13** and optionally sensing means **11**.

[0302] Thus, system **10**B can be powered by either battery power or mains power at the discretion of the user, and controller **12**B can detect the use of battery power by sensing the battery voltage via an ADC input.

11.1.2 Software Operations Performed by Controller **12**B

[0303] Controller **12**B of system **10**B executes the software operations previously described for controller **12** of system **10** when the latter is implementing asymmetric response times. Specifically, controller **12**B executes the software operations shown in FIG. **2**, modified to either: [0304] a. perform step **22**B of FIG. **4** instead of step **22** of FIG. **2** (to implement asymmetric response times via the daylight signal chain), or [0305] b. perform steps **41-43** of FIG. **5** in addition to the steps of FIG. **2** (to implement asymmetric response times via shading control logic).

[0306] These software operations, as performed by controller **12**B, are further modified in two ways.

[0307] First, the shade-opening response time is an adjustable parameter rather than a constant. Specifically, [0308] a. if asymmetric response times are implemented in the daylight signal-chain, then the time-constant of low-pass filtering step **33** (FIG. **3**) of dual-time-constant low-pass filter **30** (FIGS. **3**, **4**, and **12**) is an adjustable parameter; or [0309] b. if asymmetric response times are implemented in the shading-control logic, then interval T**2** of decision step **43** (FIGS. **5** and **13**), is an adjustable parameter.

[0310] Second, as shown in FIG. **15**, three software steps are added to enable controller **12**B to establish the shade-opening response time based on the type of power being supplied by source **90**: [0311] a. In a decision step **91**, controller **12**B branches operation to one of two paths depending on the type of power source. As previously described, controller **12**B determines the type of power source by sensing the voltage at the output of the battery supply portion of source **90**. If the voltage is zero, then mains power is inferred and operation branches to an assignment step **92**; if the voltage is non-zero, then battery power is inferred and operation branches to an assignment step **93**. [0312] b. In assignment step **92** and assignment step **93**, the shade-opening response time is set to T**2** and T**3**, respectively, with T**3** being longer than T**2**. For example, T**2** could be two minutes and T**3** could be six minutes.

[0313] The software operations of FIG. **15** can be added to those shown in FIG. **2** so that they are performed periodically while the system is operating. Alternatively, they can be performed instead as part of an initialization sequence executed whenever power is applied to controller **12**B; this is the approach used in the preferred embodiment.

[0314] Thus, system **10**B will implement a shade-opening response time of T**2** when operating under mains power, and a shade-opening response time of T**3** when operating under battery power.

[0315] This approach could be extended to make the shade-opening time-constant contingent on aspects of the system configuration other than the power source, e.g. the presence of power-consuming peripherals such as a Wi-Fi transceiver. For example, assignment step **93** could be replaced with another decision step to determine whether a Wi-Fi transceiver is present and enabled, and if so, to increase the shade-opening time-constant still further to help extend battery life.

11.2 Preferred Embodiment with Shade-Opening Response Time Based on Remaining Battery Charge

[0316] Embodiments of the subject invention which implement asymmetric response times (such as those previously described in reference to FIGS. **3**, **4**, **5**, **12**, **13**, **14**, and **15**), and which are battery-powered, can be modified to make the shade-opening response time contingent on the remaining battery charge.

11.2.1 FIG. **16**: Block Diagram of Responsive Daylight-Control System with Battery Power Supply

[0317] FIG. **16** shows a block diagram of a responsive daylight-control system **10**C which is battery powered and which is capable of automatically varying the shade-opening response time with the remaining battery charge. It is similar to system **10** of FIG. **1** except for the addition of a battery power supply **94** and the replacement of controller **12** with a controller **12**C: [0318] a. Battery power supply **94** is a conventional battery power supply that is capable of storing a charge to power system **10**C via a primary battery, a mains-rechargeable secondary battery, a solar-charged secondary battery, a secondary battery augmented with a supercapacitor or ultra-capacitor, or some other energy-storage device. [0319] b. Controller **12**C is similar to controller **12**, except that it includes conventional means of sensing the charge remaining in battery supply **94**. In the preferred embodiment, this is implemented by a conventional "coulomb-counter" integrated circuit (sometimes called a "battery fuel gauge"). Controller **12**C also includes conventional means of passing power (e.g. a power bus) from supply **94** shading device **13** and optionally sensing means **11**.

[0320] Thus, system **10**C is battery-powered and controller **12**B can sense the remaining battery charge.

11.2.2 Software Operations Performed by Controller **12**C

[0321] Controller **12**C of system **10**C executes the software operations previously described for controller **12** of system **10** when the latter is implementing asymmetric response times. Specifically, controller **12**C executes the software operations shown in FIG. **2**, modified to either: [0322] a. perform step **22**B of FIG. **4** instead of step **22** of FIG. **2** (to implement asymmetric response times via the daylight signal chain), or [0323] b. perform steps **41**-**43** of FIG. **5** in addition to the steps of FIG. **2** (to implement asymmetric response times via shading control logic).

[0324] These software operations, as performed by controller **12**C, are further modified in two ways.

[0325] First, the shade-opening response time is an adjustable parameter rather than a constant. Specifically, [0326] a. if asymmetric response times are implemented in the daylight signal-chain, then the time-constant of low-pass filtering step **33** (FIG. **3**) of dual-time-constant low-pass filter **30** (FIGS. **3**, **4**, and **12**) is an adjustable parameter; or [0327] b. if asymmetric response times are implemented in the shading-control logic, then interval T**2** of decision step **43** (FIGS. **5** and **13**), is an adjustable parameter.

[0328] Second, as shown in FIG. **17**, three software steps are added to those of FIG. **2** to enable controller **12**C to vary the shade-opening response time based on remaining state of charge of battery power supply **94**: [0329] a. In a step **95**, controller **12**C senses the remaining battery charge and compares it to a threshold. If the charge is above the threshold, the battery state is deemed "ok" and operation branches to an assignment step **96**. Otherwise, if the charge is below the threshold, the battery state is deemed "low" and operation branches to an assignment step **97**. [0330] b. In assignment steps **96** and **97**, the shade-opening response time is set to T**3** and T**4**, respectively, with T**4** being longer than T**3**. For example, T**3** could be six minutes and T**4** could be fifteen minutes.

[0331] Thus, system **10** will implement a shade-opening response time of T**3** when the battery charge is nominal, and a shade-opening response time of T**4** when the battery charge is low.

11.3 Preferred Embodiment with Shade-Opening Response Time Varying as an Arbitrary Function of Remaining Battery Charge

[0332] When system **10**C of FIG. **16** performs the additional software operations shown in FIG. **17**, it implements one of two shade-opening response times as a function of the remaining battery charge. Alternatively, it could implement a response time which is as arbitrary function of the remaining charge. This would be achieved by replacing steps **95**, **96**, and **97** of FIG. **17** with steps to: [0333] a. sense the remaining charge, and [0334] b. calculate a value of the shade-opening response time as a function of that value.

[0335] A variety of potentially useful functions are possible. For example, the shade-opening response time could increase continuously and linearly with decreasing battery charge.

[0336] Alternatively, it could increase continuously until the battery charge drops to a predetermined value, at which point the shade-opening response time could be set to a very large value to completely inhibit shade-opening adjustments until the battery is charged or replaced. This would preserve glare-blocking capability (by allowing shade-closing adjustments) while also providing a clear indication of the need to charge or replace the battery.

[0337] A function in which the shade-opening response time increases continuously with decreasing battery charge is particularly advantageous when the battery supply **94** includes a solar-charged battery, because it enables system **10**C to automatically optimize the shade-opening response time based on the average power output of the photovoltaic source.

11.4 Advantages of Shade-Opening Response Time Adjusted to Maximize Battery Life

[0338] The embodiments described in reference to FIGS. **14-17** can extend battery life in battery-powered responsive daylight-control systems without sacrificing responsiveness in blocking daylight glare. The increase in battery life is particularly significant in systems in which the power consumed in shading adjustments is a significant fraction of the overall power consumption. Such systems include those which do not have wireless connectivity (which often dominates the overall power consumption), or those in which a low-power protocol (such as Zigbee/Thread or BLE) is used for wireless connectivity.

12 Preferred Embodiment with Slow-Response Shade-Opening in Sustained Daylight Fluctuation

[0339] The embodiments of responsive daylight control system **10** described in reference to FIGS. **6-13** completely inhibit shade opening adjustments in the presence of sustained daylight fluctuation.

[0340] However, while this eliminates the risk of frequent shading adjustments during sustained fluctuation, it also causes the shading to remain excessively closed even while the average irradiance drops significantly as the sun descends toward the horizon.

[0341] This effect can be mitigated by enabling shade-opening adjustments in the presence of sustained daylight fluctuation—but with a much longer response time than when there is no sustained fluctuation. System **10** of FIG. **1** can implement such a capability through modification of estimation step **22** of FIG. **2**.

[0342] FIG. **18** is a logic diagram of such a modified estimation step, an estimation step **22**E, which is implemented in software steps executed by controller **12** of FIG. **1**. Step **22**E subsumes step **22** of FIG. **2**, preceding it by three functional blocks: fluctuation detector **50** (previously described in reference to FIG. **8**), a time-constant logic block **101**, and a Low-Pass Filter (LPF) **102**.

[0343] LPF **101** is a conventional parameterized low-pass filter. It low-pass filters the output of daylight sensing means **11** of FIG. **1** (as sampled after pause step **21** of FIG. **2**) with a time-constant which is determined by a time-constant parameter. In the preferred embodiment, LPF **101** is implemented as a conventional Exponentially Weighted Moving-Average (EWMA) filter, with the effective time constant set by an EWMA weighting parameter. The output of LPF **101** drives

daylight-estimation step **22** previously described in reference to FIG. **2**.
[0344] Time-constant logic block **102** determines the value of the time-constant parameter of LPF **101** as a function of the output of fluctuation detector **50** and the output of daylight sensing means **11** of FIG. **1**. FIG. **19** is a flowchart of steps performed in time-constant logic block **102**: [0345] a. In a decision step **103**, operation branches depending on whether there has been a change in the daylight level, and if so, depending on the sign of the change. If there is no change, no other steps are performed in block **102**. If there has been a positive change (i.e. the daylight level has increased), an assignment step **105** is performed in which a time constant parameter T is set to a value TA. However, if there has been a negative change, operation branches to a decision step **104**.
[0346] b. In decision step **104**, operation branches depending on the presence of fluctuation (i.e. as indicated by the output of fluctuation detector **50** of FIG. **17**). If there is no fluctuation, an assignment step **106** is performed in which T is set to TB, but if there is fluctuation, an assignment step **107** is performed in which T is set to TC.
[0347] Thus, daylight-estimation step **22**E provides a low-pass-filtered estimate of the daylight level, such that there is a low-pass filtering time constant of TA for increases in daylight, a time-constant of TB for decreases in daylight when there is no fluctuation, and a time-constant of TC for decreases in daylight when there is fluctuation.
[0348] Because TA determines the response time for shade-closing adjustments, it is analogous to the time-constant of LPF **1** of FIG. **3** and to interval T**1** of FIG. **5**. As previously described for LPF **1** and interval T**1**, TA should be no longer than several seconds in order to enable system **10** to close the shading quickly to block daylight glare.
[0349] Because TB determines the response time for shade-opening adjustments when there is no sustained fluctuation, it is analogous to the shade-opening time-constants of the embodiments previously described in reference to FIGS. **12** and **13**. TB should be long enough to limit the frequency of shading adjustments when the fluctuation level is too low to be detected by fluctuation detector **50**, but not so long as to cause an excessive delay in opening the shading in response to falling daylight levels. A value of several minutes has proven effective for TB.
[0350] Time-constant TC determines the response time for shade-opening adjustments during sustained fluctuation. TC should be as long as possible while still allowing the output of LPF **101** to track the relatively slow decreases in peak irradiance due to movement of the sun as it descends from maximum elevation toward the horizon. To date, values of approximately 15 to 120 minutes have proven effective for TC.

12.1 Alternative Embodiment with TB Contingent on Type of Power Source and/or Remaining Battery
Charge

[0351] While a fixed value (e.g. a few minutes) can be used for TB as described above, it is also potentially advantageous to make TB contingent on the type of power source and/or the remaining battery charge, as previously described for the embodiments of FIGS. **14** through **17**. In this case, TB could be set to either T**2** or T**3** of FIG. **15** depending on the type of power source, or either T**3** or T**4** of FIG. **17** depending on the level of remaining charge, as described for the corresponding embodiments.

12.2 Alternative Embodiments of Fluctuation Detector **50**

[0352] As previously described in reference to FIG. **8**, fluctuation detector **50** uses full-wave rectification to sense the fluctuation power. This maximizes sensitivity to fluctuation, but causes the fluctuation signal to be falsely asserted when the irradiance drops at sunset, unnecessarily delaying shade opening. This can be avoided by using half-wave rectification to detect only increases in the daylight level.
[0353] Alternatively, any of the other fluctuation detector embodiments described herein (such as those of FIGS. **9-11**) could be used instead of fluctuation detector **50**.

12.3 Advantages of Enabling Slow-Response Shade Opening in Sustained Fluctuation

[0354] When system **10** of FIG. **1** is modified as described in reference to FIGS. **18** and **19**, it allows the shading to open during sustained fluctuation, but the increased shade-opening response time causes the shading to open only in response to the slow, non-problematic fluctuation associated with changes in the solar elevation angle. It thereby avoids the over-shading that would otherwise occur if shade opening were completely inhibited during problematic fluctuation in the afternoon, while still avoiding excessively frequent shading adjustments.

13 Preferred Embodiment of Fluctuation Detector with Reduced Release Time after Isolated Fluctuations

[0355] The purpose of the fluctuation detectors described herein is to continuously assert a fluctuation signal during sustained problematic fluctuation due to moving clouds, and ideally only during such fluctuation. In fluctuation detector **50** of FIG. **8**, this is accomplished by optimizing the averaging interval of averager block **55**, and optionally including pulse stretcher **57** to extend the duration of the signal as necessary.

[0356] However, because fluctuation detector **50** employs broadband amplitude demodulation (via rectification of the daylight signal), any change in the daylight irradiance—not just during sustained fluctuation due to moving clouds, but also due to movement of the sun—will contribute to the fluctuation energy accumulated in averager block **55**. If the irradiance then falls, the accumulated fluctuation energy will cause fluctuation detector **50** to continue to assert the fluctuation signal for an interval referred to herein as the release time, thereby delaying shade opening.

[0357] While an extended release time is desirable during sustained problematic fluctuation, it is undesirable during isolated fluctuations. Isolated fluctuations occur, for example, when the rising sun is obscured by buildings, or when the moving sun emerges from behind a building and is then obscured by other buildings. Ideally, the shading would be opened quickly after such isolated fluctuations, but due to the release time necessary to span problematic fluctuations, fluctuation detector **50** will continue to assert the fluctuation signal for an unnecessarily long interval after the irradiance falls, excessively delaying shade opening.

[0358] This can be mitigated by basing the fluctuation signal on only the positive fluctuation (i.e. increases in the daylight level) as low-pass filtered with a time-constant (or averaged over an interval) which depends on the amount of negative fluctuation (i.e. decreases in the daylight level). This enables a suitably long release time during sustained fluctuations (ensuring that the fluctuation signal remains asserted continuously), but a suitably short release time during isolated fluctuations (ensuring that the fluctuation signal is de-asserted quickly after the daylight level falls).

[0359] Such a fluctuation detector could be implemented in hardware, but (as with fluctuation detector **50**) is preferably implemented via software operations executed by controller **12** of FIG. **1**. FIG. **20** is a flowchart to implement a preferred embodiment of such a fluctuation detector **50**E, which includes the following functional blocks: [0360] a. Differentiator block **53** (previously described in reference to FIG. **8**) performs differentiation with respect to time of the signal on input **51** in order to pass only the time-varying component thereof. Thus, the output of block **53** is positive for increases in the signal on input **51** and negative for decreases thereof, with the magnitude depending on the rate of increase or decrease. [0361] b. A positive half-wave rectifier **111** and a negative half-wave rectifier **112** perform half-wave rectification of the output of block **53**: rectifier **111** passes only positive outputs of block **53** as positive signals, while rectifier **112** passes only negative outputs of block **53** as positive signals). Thus, rectifiers **111** and **112** detect the positive and negative amplitudes, respectively, of the fluctuation. Rectifiers **111** and **112** can be implemented, for example, via conditional mathematical operators (and a sign change to invert the output of rectifier **112**). Rectifier **111** feeds an averager **113**, while rectifier **112** feeds an averager **115**. [0362] c. Averager **113** averages the output of rectifier **111** over a first averaging interval which depends on a signal **114**. Averager **113** can be conveniently implemented, for example, as a conventional first-order Exponentially Weighted Moving Average (EWMA) filter, with a single weighting parameter which varies with signal **114**. The relationship between signal **114** and the first averaging interval can be linear or non-linear as required to achieve the desired behavior described below; a linear relationship has worked well in prototypes of detector **50**E. [0363] d. Signal **114** is the output of averager **115**, which averages the output of negative half-wave rectifier **112** over a second averaging interval. Averager **115** can be implemented in the same way as averager **113**, although it does not require a variable averaging interval. [0364] e. Comparator block **56** (previously described in reference to FIG. **8**) asserts the "fluctuation" signal when the output of averager **113** exceeds a threshold, and de-asserts the "fluctuation" signal when the output of averager **113** drops below a threshold.

[0365] Thus, fluctuation detector **50**E functions in much the same way as fluctuation detector **50** of FIG. **8**, with positive half-wave rectifier **111** being analogous to full-wave rectifier block **54** and averager **113** being analogous to averager block **55**. However, instead of using a fixed averaging interval (as is the case with averager block **55** of detector **50**), averager **113** has a variable averaging interval which depends on the average negative fluctuation as sensed by rectifier **112** and averager **115**. Thus, the positive fluctuation is low-pass filtered with a relatively long time-constant when there is substantial average negative fluctuation (e.g. during sustained fluctuation), but with a relatively short time-constant when there is little average negative fluctuation (e.g. while the irradiance is rising slowly prior to an isolated fluctuation event).

[0366] The averaging interval of averger **115**, and the relationship between the output of averager **115** (i.e. signal **114**) and the variable averaging interval of averager **113**, should be chosen to yield the following behavior: [0367] a. During problematic fluctuation with repeated significant decreases in the daylight level, the variable averaging interval of averager **113** should be long enough (e.g. 10 minutes) to ensure that the fluctuation signal produced by comparator **56** remains asserted continuously. [0368] b. After a single isolated decrease in the daylight level, the variable averaging interval of averager **113** should be short enough (e.g. 1 minute) to provide an acceptably short delay in de-asserting the fluctuation signal.

[0369] Fluctuation detector **50**E can be used instead of, and in the same way as, any of fluctuation detectors **50** and **50**B-**50**D of the previously-described embodiments of the subject invention.

13.1 Advantages of Reduced Release Time after Isolated Fluctuations

[0370] Isolated fluctuations in the daylight level occur much less frequently than sustained fluctuations. However, when they do occur, any delay in shade-opening adjustments following a decrease in irradiance is quite noticeable to building occupants. Therefore, the reduced release time after isolated fluctuations enabled by fluctuation detector **50**E should significantly increase occupant satisfaction with responsive daylight control, and testing to date has confirmed this.

13.2 Alternative Embodiments of Fluctuation Detector **50**E

[0371] A wide range of alternative embodiments of fluctuation detector **50**E are possible while still retaining the key principle of fluctuation detection based on positive fluctuation which is averaged over an interval which depends on negative fluctuation.

[0372] As with any device, the implementation of fluctuation detector **50**E represents a trade between ease of implementation and performance (i.e. sensitivity to problematic fluctuation and insensitivity to non-problematic fluctuation). The above-described embodiment is intended to maximize ease of implementation while still providing good performance, but a more complex embodiment could provide still better performance.

[0373] For example, rectifiers **111** and **112** are implemented using simple conditional operators (and a sign inversion in the case of rectifier **112**), so their outputs vary with the amplitudes of the positive and negative fluctuations (respectively). Increased reliability of fluctuation detection might be possible if rectifiers **111** and **112** were modified to have a non-linear response to fluctuation amplitude (such as a square-law response to directly sense the fluctuation power, or a logarithmic response to provide greater dynamic range).

[0374] As another example, differentiator block **53** is simple form of first-order high-pass filter, while averagers **113** and **115** are simple forms of first-order low-pass filter. A higher-order high-pass filter, and/or a high-pass filter of another form, could be used instead of differentiator block **53** and might enable increased performance. Similarly, a higher-order low-pass filter, and/or a low-pass filter of another form (such as a lossy integrator), could be used instead of either or both of averagers **113** and **115** and might enable increased performance. However, the broadband spectral characteristics of problematic fluctuation suggest that any benefit of more complex filters would be modest.

[0375] As another example, fluctuation detector **50**E of FIG. **20** could include a machine-learned model which performs all or some of the functions of the elements shown in FIG. **20**.

14 Additional Implementation Considerations and Alternatives

14.1 Use with Devices Other than Motorized Horizontal Blinds

[0376] As previously stated, shading device **13** is advantageously a horizontal blind with a motorized slat-tilt function. Such motorized blinds are preferred for responsive daylight control applications due to their low cost, unobtrusive operation, and fine control of admitted daylight.

[0377] However, because the subject invention enables a reduction in the frequency of shading adjustments needed for responsive daylight control, it can also enable the use of shading devices which are more obtrusive in operation and provide coarser control of admitted daylight, such motorized curtains and shades.

[0378] Because such shading devices are more obtrusive in operation than motorized blinds, their use as shading device **13** will typically require a longer shade-opening response time (and potentially a longer shade-closing response time), and typically a larger deadband (e.g. as evaluated in decision step **24** of FIG. **2**), than if a motorized horizontal blind were used.

14.2 Increasing the Shade-Closing Response Time in Addition to the Shade-Opening Response Time

[0379] According to the subject invention, increasing the shade-opening response time is preferable to increasing the shade-closing response time as a means of reducing the frequency of shading adjustments needed for responsive daylight control. This is because responsiveness to rising daylight levels (i.e. to quickly block daylight glare) is typically more important than responsiveness to falling daylight levels.

[0380] If there is little risk of daylight glare, however, it may be advantageous to increase the shade-closing response time in addition to increasing the shade-opening response-time. This can be the case, for example, with a shading device mounted on a window which never receives direct sunlight. In such cases, the embodiments of system **10** described above can be modified to increase the shade-closing response time in the same way as the shade-opening response time is increased.

14.3 Optimization of Parameter Values

[0381] The parameter values cited in this disclosure have proven to be workable in useful embodiments of the subject invention, but are not necessarily optimal. Practitioners can use the information provided herein to optimize the values for a given application, preferably empirically.

14.4 User-Selectable Parameter Values

[0382] In lieu of optimizing the parameter values prior to usage of a responsive daylight-control system according to the subject invention, the numerical values of the parameters could be made user-adjustable via a conventional user-system interface.

[0383] For example, a user interface could be provided to enable a user to explicitly specify the shade-opening and shade-closing response times, incrementally increase or decrease the response times, or indirectly specify the response times by selecting from a menu of predefined usage variables. In the latter case, the predefined usage variables could include the following: [0384] a. Whether the window on which the shading device is mounted can receive direct sunlight. If the window cannot receive direct sunlight, then a longer shade-closing response time may be appropriate, since there is no risk of extremely high glare. [0385] b. The type of shading device. If the shading device is a smart window, the optimum shade-opening response time will typically be shorter than for a motorized horizontal blind (per the previously-described embodiment of shading device **13**). On the other hand, if the shading device is a roller shade, then the optimum shade-opening response time will be longer than for a motorized horizontal blind, and longer still if the shading device is a motorized curtain. The optimum shade-closing response time will also vary with the type of shading device, but to a lesser degree. [0386] c. The power source. As previously described, a battery-powered system can benefit from a longer shade-opening response time to maximize battery life.

14.5 Distribution of Functions or Elements Among Separate Locations or Physical Devices

[0387] Referring again to FIG. **1**, sensing means **11**, controller **12**, and shading device **13** need not necessarily be collocated, but could instead be in separate locations and interconnected by wired or wireless links. For example, [0388] a. Controller **12** could be collocated with shading device **13**, but sensing means **11** could be in a remote sensor assembly connected to controller **12** via a wireless protocol such as Zigbee or Thread. [0389] b. When sensing means **11** is implemented as a remote sensor assembly as described above, then some of the functionality provided by controller **12** can advantageously be provided by a processor in the same remote sensor assembly. For example, the portion of controller **12** which performs steps related to estimating the daylight level (such as steps **21** and **22** of FIG. **2**, step **22**B of FIG. **4**, step **22**C of FIG. **6**, or step **22**D of FIG. **12**) could be integrated in the same remote sensor assembly with sensing means **11**. Thus, an existing responsive daylight-control system intended for use with a remote sensor assembly could be upgraded into an embodiment of the subject invention by simply replacing the conventional sensor assembly. [0390] c. A portion (or all) of controller **12** could be "in the cloud", i.e. implemented on a server connected to sensing means **11** and shading device **13** via the internet through a gateway. [0391] d. A portion (or all) of controller **12** could be incorporated in a home-automation hub, voice-assistant, building-management system, desktop computer, or personal electronic device.

14.6 Implementation via Software-Only Modifications to Conventional System

[0392] As previously described in reference to FIG. **1**, the hardware configuration of system **10** according to the subject invention is consistent with that of a conventional responsive daylight-control system. Thus, the subject invention could be implemented solely via modifications to the software (or firmware) of such a conventional system to implement the operating steps described herein.

15 Conclusions, Ramifications, and Scope

[0393] As this disclosure makes clear, the subject invention enables a responsive daylight control capability which responds quickly to the onset of glare-inducing conditions and reasonably quickly to the cessation of glare-inducing conditions, and yet which avoids excessively frequent shading adjustments (and especially closely-timed adjustments in opposite directions). The subject invention thus enables a capability which provides the benefits of conventional responsive daylight-control systems, but without the conventional systems' tendency to annoy building occupants and with reduced power consumption. In doing so, the subject invention eliminates a significant barrier to mainstream use of responsive daylight-control technology.

[0394] Those skilled in the art will recognize that the construction, function, and operation of the elements composing the preferred and alternative embodiments described herein may be modified, eliminated, or augmented to realize many other useful embodiments, without departing from the scope and spirit of the invention as disclosed herein and recited in any appended claims.

Claims

1. A system for automatic control of daylight, said system including: a. an electronically-actuated shading device; b. daylight-sensing means for sensing a level of daylight; and c. a controller configured to: i. close said shading device after a first response time after an increase in said level of daylight; and ii. open said shading device after a second response time after a decrease in said

level of daylight, said second response time being greater than said first response time.
2. The system of claim 1 which further includes fluctuation-detecting means for detecting a fluctuation in said level of daylight, and wherein said controller is configured to increase said second response time when said fluctuation is detected.
3. The system of claim 2 wherein said fluctuation-detection means includes an amplitude demodulator.
4. The system of claim 2 wherein said fluctuation-detection means includes an application-programming interface to a source of weather data.
5. The system of claim 2 wherein said fluctuation-detection means includes: a. first sensing means of sensing an increase in said level of daylight to produce a positive fluctuation signal; b. second sensing means of sensing a decrease in said level of daylight to produce a negative fluctuation signal; and c. filtering means of low-pass filtering said positive fluctuation signal with a time-constant which depends on said negative fluctuation signal.
6. The system of claim 1 which can be configured to accept power from a one of a plurality of power sources including a battery, and in which said controller is configured to increase said second response time when said system is configured to accept power from said battery.
7. The system of claim 1 which is configured to accept power from a battery and which further includes charge-sensing means for sensing a level of charge of said battery, and in which said controller is configured to increase said second response time with a decrease in said level of charge.
8. A system for automatic control of daylight, said system including: a. an electronically-actuated shading device; b. daylight-sensing means for sensing a level of daylight; c. fluctuation-detection means for detecting a fluctuation of daylight; d. a controller configured to: i. perform an opening of said shading device following an decrease in said level of daylight; ii. perform a closing of said shading device following an increase in said level of daylight; and iii. inhibit said opening of said shading device when said fluctuation is detected.
9. The system of claim 8 wherein said fluctuation-detection means includes an amplitude demodulator.
10. The system of claim 8 wherein said fluctuation-detection means includes an application-programming interface to a source of weather data.
11. The system of claim 8 wherein said fluctuation-detection means includes: a. first sensing means of sensing an increase in said level of daylight to produce a positive fluctuation signal; b. second sensing means of sensing a decrease in said level of daylight to produce a negative fluctuation signal; and c. filtering means of low-pass filtering said positive fluctuation signal with a time-constant which depends on said negative fluctuation signal.
12. A system for automatic control of daylight, said system including: a. an electronically-actuated shading device; b. daylight-sensing means for sensing a level of daylight; c. a battery, said battery having a level of charge; and d. a controller configured to actuate said shading device after a response time following a change in said level of daylight, wherein said response time depends on said level of charge of said battery.