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Article

Prototype of Automated Shading Device: Preliminary Development

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Abstract. Located in the equator zone, Indonesia receives intense solar radiation throughout the day with the average daily solar radiation around 4 kWh/m^2. Thus, shading devices particularly movable shading device play an important role to reduce the effects of solar radiation. This study aims to develop external automated shading devices horizontally, the results of the performance test for mechanical and control systems only were reported in this paper. These systems consist of four primary components; window frames and panes, mechanical system, sensors and acquisition data system, and control system. Window frame used Manglid (*Manglieta glauca*) wood while the windowpanes were developed from corrugated plastic sheet. As a mechanical system, the DC motor stepper with a torque value of 3.6Nm was used as an actuator device to change the rotation angles of the panes. Instead of solar radiation sensor, the TSL2561-illuminance sensor was applied due to its affordability. It was integrated to a microcontroller device (Arduino Mega 2560) and the Arduino IDE was employed to input its algorithms. The control system contained a set of algorithms that enabling the windowpanes to move according to the illuminance received by the sensor and the sun path data input to the program. The two respective performance tests were conducted in the laboratory by illuminating the sensor using an artificial light source and installed the shading device on the test house under actual condition. The results demonstrated that the mechanical and control systems worked properly, and they were synchronized. The accuracy of the sensor was about 53.2–85.8 and the response time for the actuator was less than 3 seconds.

Keywords: Automated shading devices, control system, microcontroller Arduino, illuminance, indoor thermal environment.

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1. Introduction

The tropical region is an uncomfortable climate zone characterized by receiving intense solar radiation throughout the year, having high annual mean air temperature, small and constant diurnal air temperature throughout the year, very high levels of air humidity and long periods of sunny days throughout the year [1-3].

Those climate factors affect the building design in the tropical regions in order to achieve better indoor thermal performance. The investigation results of Givoni [1] and Koenigsberger et al. [4] showed that providing sun protection on tropical building can achieve a significant improvement to indoor thermal and visual comfort. For low-income housing in the tropics, utilisation of shading devices could improve thermal comfort although they are not sufficient to achieve thermal comfort standard [5]. Moreover, shading devices in both ventilated and unventilated rooms have a significant impact on improving indoor thermal comfort in the tropics [6]. Similar finding also summarized by Freewan [7] for the office buildings in the hot climatic region. Study by Lau et al. [8] recommended to apply shading devices on facades of high-rise office buildings in hot-humid Malaysia to save more energy. The above studies implied that the shading device is one of the important techniques for tropical building design. Thus, the use of shading device is essential part of the building envelope to reduce the heat transfer from the outside to inside, particularly in the region with high intensity of solar radiation.

Shading device, particularly external shading device can be fixed or movable. Generally, a movable shading device is equipped with a sensor, motor, and other components and able to move based on the stimuli received. In regard to shading devices, more attentions have been paid to preventing direct solar radiation alone despite the sky and diffuse radiation contribute to solar heat gain [9]. Meanwhile, fixed-type shading device in some ways effectively blocks the direct solar radiation instead of the sky or diffuse solar radiation. Movable shading device thus is important to resolve above problems.

The impact of external shading device on indoor environmental performance has been broadly discussed [7-14] and some of them concluded that a movable shading device has better performance compared to the fixed-type. For instance, a certain proposed solar shading control strategy can achieve indoor environmental performance (i.e., thermal and visual comfort) standard and reduce the energy use of building [10]. Through computer simulation, Kim et al. [11] figured out that external shading devices is much more effective than the internal shading devices since the latter absorbs the solar heat and reradiate to the indoor space. Moreover, the largest energy saving is achieved when the external shading device equipped with the slats with the angle of 60°. In another study, the use of movable shading device can reduce the energy consumption of 9.8 percent per year [12].

Up to date, several technologies of movable shading devices are available including automated movable shading devices. In their review, Dakheel and Aoul the use of robotic controlling systems and the thermo-hydraulic controlling systems are emerging, although requires further investigation as there are limited number of studies done on their performance, building application and use in varying climate conditions [15]. They reviewed that the current automated shading devices were mainly categorized into rotating shading and folding shading systems. Even several years ago, Guillemin and Molteni [16] developed an algorithm for controller of the shading devices self-adapting to the user wishes. Al-Masrani and Al-Obaidi [17] present the review for the current status of the development of the active and dynamic shading systems, including new technologies based on reactive system, autonomous system and agent system. They reviewed deeply each technology, methods, materials and also thermal performance. The use of sun-tracker as main component of movable shading devices also discussed and at the same time installed with solar panel [18, 19].

This study is one of attempts to develop the automated shading devices specifically for the tropical buildings by using affordable components. This study proposes a control algorithm, acquisition data system, and mechanical system for automated external shading device. The system consists of four primary components; window frame and windowpane, mechanical system, sensor and

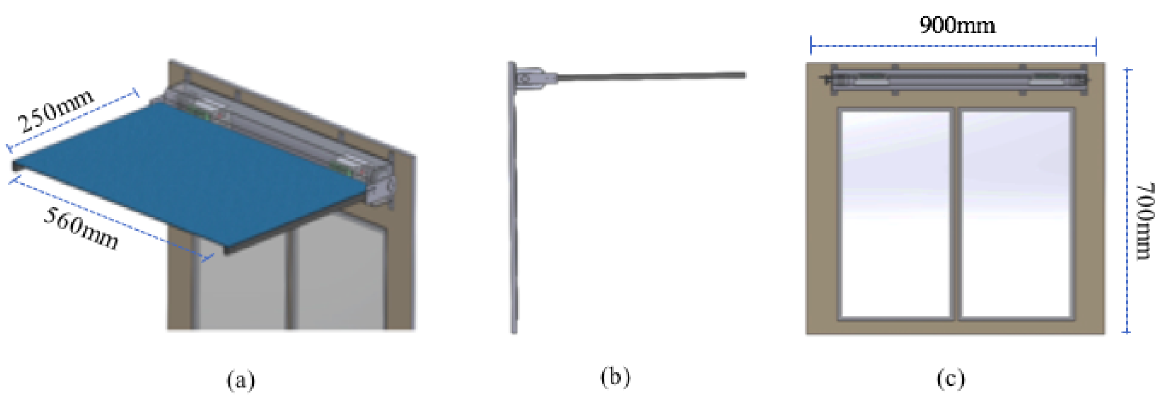


Fig. 1. Automated shading device design: (a) isometric view; (b) side view; (c) front view.

acquisition data system, and control system. Evaluation of this system's performance as well as future development based on the evaluation test are presented in this paper. It should be noted that the evaluation was carried out for mechanical and control systems alone to verify the performance of some parameters such as mechanical system performance, sensor accuracy, response time, and the algorithm.

2. Materials and Methods

Prototypes of horizontal automated shading devices have been developed. As previously mentioned, the prototypes concise of four main systems and those four systems should work together in a proper way. Therefore, the design of those systems should be considered carefully.

2.1. Physical and Mechanical System

As can be seen in Fig. 1, the physical components of the prototypes mainly consist of the window frame and windowpane. The windowpane was made from corrugated plastic sheet with thickness of 4mm and total area of 560mm×250mm. This plastic sheet was used because of its lightweight and therefore it reduces actuator's lifting load. Meanwhile, the window frame used Manglid wood (*Manglieta glauca*) since it is strong, durable, and relatively light. This frame had thickness of 20mm and the total area of 900mm×700mm for the horizontal shading device. Manglid wood was classified into class II for its durability and class III for its strength. Class II of durability indicates that Manglid would remain unbreakable up to five years under normal outdoor condition [20] while Class III of strength implies that the flexural strength of this wood was ranged from 500-725kg/cm^2 under condition of dry air density of 0.40-0.60. In addition, this kind of wood is abundantly available in Indonesia, particularly in West Java and Bali.

For the mechanical system, instead of DC servo motor, the DC motor stepper with a torque value of 3.6Nm was employed as an actuator due to its affordability, excellent repeatability, stability, safety and simplicity of setup and usage. It enables to move the load up to 1.2kg. In this system, the total mass to be lifted was around 0.6kg including windowpane, hinges, and connectors of automated shading devices. Although the stepper motor has lower speed than the other DC motor types, but its speed performance is still in accordance with the system requirements. The main function of the actuator is to change the rotation angles of the windowpane.

2.2. Sensors and Acquisition Data System

In this study, two control systems were investigated, they are control mode based on the solar radiation received by the sensor (hereafter namely Mode 1) and by sun path diagram data of Bandung (hereafter namely Mode 2). Bandung was chosen since the experimental test houses for implementing the movable shading device is constructed in this city. Solar radiation is the main measure for the automated shading device for the Mode 1. The device is moving based on the solar radiation received by the sensor. A set of a sensor and data acquisition systems are required and thus the selection of appropriate sensor and the design of data acquisition system play important role in this device. Ideally, solar radiation sensor (i.e. Pyranometer) should be used for the accuracy reason. Since this sensor is quite expensive, the alternative sensor should be considered. The TSL2561-illuminance sensor

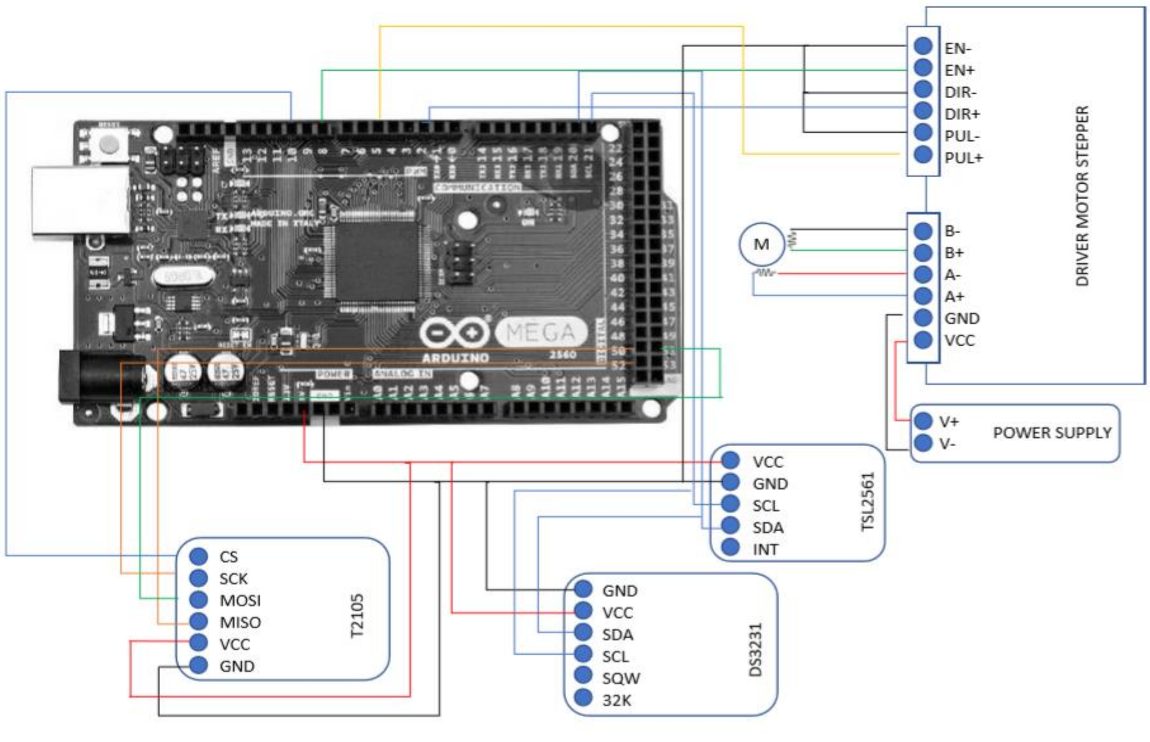


Fig. 2. Configuration of sensors and acquisition data system.

Table 1. Specification of sensor and acquisition data devices.

Feature	Information
Arduino	
Operating voltage [V]	5
Digital I/O Pins	54
Analog Input Pins	16
SRAM [KB]	8
EEPROM [KB]	4
Clock speed [MHz]	16
TSL2561-illuminance sensor	
Power supply [V]	3.3 - 5
Light ranges [lux]	0.1 - 40000
Low supply current max [mA]	0.6
T2105-micro SD card reader writer	
Power supply [V]	5
Current [mA]	80
Interface power supply [V]	3.3 – 5
Card type	Micro SD Card (≤ 2GB)/ Micro SDHC Card (≤ 32GB)
DS3231-real time clock	
Operating voltage [v]	2.3 – 5.5
Operating temperature [°C]	-45 to +80
Clock accuracy [ppm]	+2 to -2 for 0°C to 40°C; +3.5 to -3.5 for -40° C to +85°C
Battery lifetime [years]	3
Motor stepper	
Power supply [V]	24 – 50
Current supply [A]	4
Torque [Nm]	3.6
Shaft diameter [mm]	8
Shaft length [mm]	23

with the illuminance range of 0.1-40.000 lux was selected and applied in this system simply because its affordability (see Table 1). In addition, the solar radiation can be represented by the illuminance value, where the typical conversion value for 1 W/m² of solar radiation is 100lux depend on the geographical situation [3]. Moreover, the TSL2561-illuminance sensor is easy to use and setup with the required power supply around of 5V.

The illuminance received by sensor is saved in the memory card and at the same time transferred into a microcontroller Arduino (see Fig. 2). There are different types of Arduino's hardware due to the control chip used and the number of board pins. The selection of Arduino thus is a pivotal step in designing control system for shading device since it should accommodate the system requirements, i.e., digital input/output pins, memory capacity, and processing speed. As previously described in Subsection 2.2, the system mainly required 22 pins to integrate several components (i.e., sensor, motor, memory card, real time clock) and bigger memory capacity considering its performance to continuously process data for one full day. Based on those requirements, Arduino Mega 2560 was used because it has sufficient number of pins and the memory capacity for the requirements.

Since the device movement in Mode 2 based on the altitude data from sun path diagram, a set of illuminance sensor is no longer necessary. The sun path diagram is

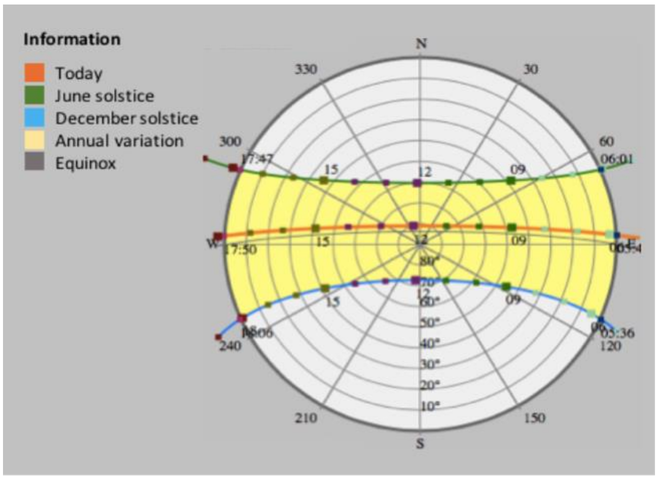
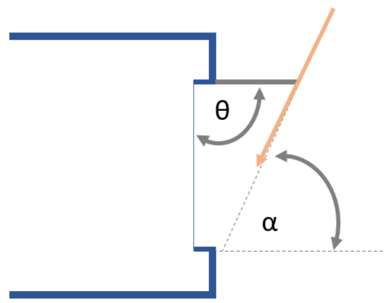


Fig. 3. Sun path diagram of Bandung.

shown in Fig. 3 while the angle movements based on those sun elevations are indicated in Table 2. Astronomically, Bandung is located in southern hemisphere at 6°54'S and 107°36'E. In this mode, the system consists of Arduino as microcontroller, DS3231-real time clock as a variable of windowpane's movement angle, T2105-micro SD card writer and motor stepper. Window pane angles were manually calculated based on the pane geometry and the sun elevation at the certain time for every 15 minutes. This duration was determined because the solar radiation enter the room after 15 minutes. The definition of the movement angle is illustrated in Fig. 4.



α : sun's altitude
θ : windowpane's angle

Fig. 4. Test configuration for Mode 2.

Table 2. Windowpane's angle movement based on sun path diagram.

Time	Sun's elevation (°)	Window pane angle (°)
16:00	47	85
16:15	43	74
16:30	40	66
16:45	36	53
17:00	32	35
17:15	29	29
17:30	25	25
17:45	22	13
18:00	18	90
18:30 – 15:59		90

2.3. Control System

The control process was implemented using the Arduino IDE to input the algorithm of the microcontroller device (i.e., Arduino Mega 2560). The control system basically contained a set of algorithms that enable the windowpanes to move according to the illuminance received by the sensor. In Mode 1, the control processes involving three different phases. In the first phase, the illuminance from the lighting source (i.e. the sun) received by the sensors (TSL2561) was calculated by the Arduino. Next, the illuminance value representing solar radiation value became input to program movement angle of motor stepper. In this work, the illuminance was converted into particular moving angle of the motor stepper. When the received illuminance value exceeded the threshold values (for instance, 500 lux), the microcontroller responded by sending an order to the actuator (i.e., motor stepper) to move up or down the panes accordingly. In the last phase, the calculated stepper angle from the previous phase then translated into movement and executed by the motor stepper.

As previously described, the Mode 2 works solely depend on the data of the windowpane angles that input to the microcontroller. To prevent the excessive radiation, the sun elevation is an important variable to calculate the windowpane's angle. As shown in Table 2, the different window pane angles were set at different time. When the real time clock indicates a certain time, the microcontroller sends an order to the actuator to move down the pane according to the sun's position. For instance, when the clock indicates 16.00, the window pane moves down 15° and form the angle of 85° from the normal line.

2.4. Test Configuration

To evaluate the performance of the automated shading devices, the test was performed in the Laboratory of Building Sciences, Research Institute for Housing and Human Settlements, Bandung at 29 March – 01 April 2019. The test focused on the ability of each component work properly and synchronize each other. The test was carried out with the aims to assess the performance of the shading device including the sensor's accuracy, effectiveness of sensor's placement, control algorithms,

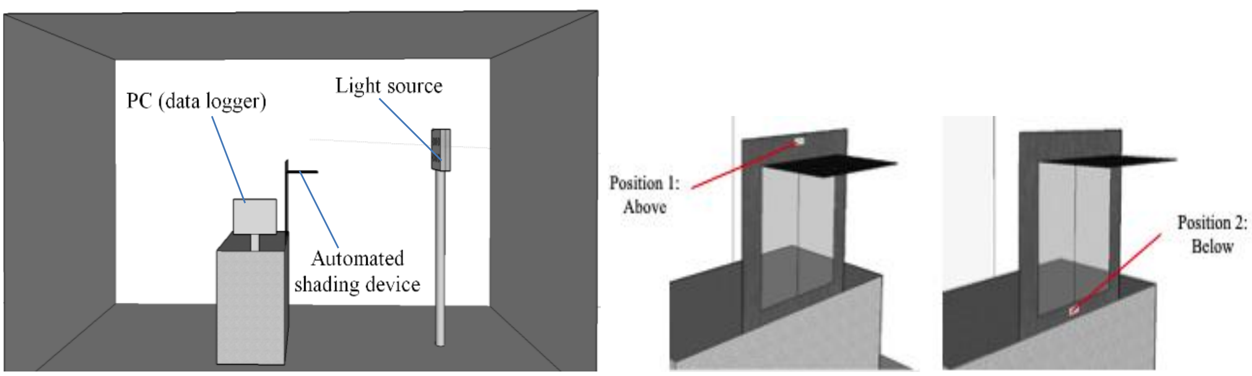


Fig. 5. Mode 1's performance test configuration.

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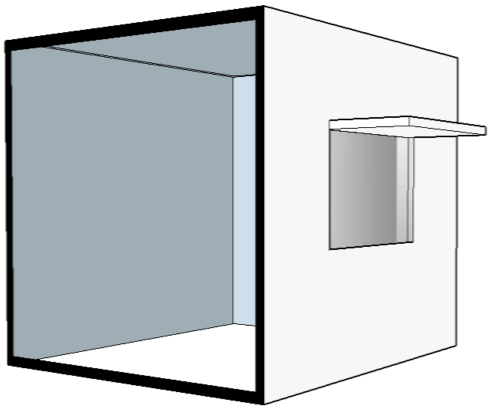

Fig. 6. Test configuration for automated shading device under Mode 2 in the test house.

and the mechanical performance. In the Mode 1, the source of illuminance was obtained from the five artificial lighting sources with the capacity of each was 0.4 kVA. Each light bulb has output lumen of 670 lumen corresponded to the color temperature of 2700K. The main parameter to be evaluated was the response of the system on the received illuminance. This amount of illuminance value was set by varying the number of light bulbs.

Figure 5 illustrated the test configuration in a dark room. The illuminance from the outside was blocked completely from entering the room. As indicated, the both illuminance sensors were placed 1m away from the light source. In addition to TSL2561-illuminance sensor, the analog luxmeter was attached to the system to measure the illuminance. This analog luxmeter has a maximum range of 3000lx with the accuracy about ±7% of reading. These sensors were placed on the upper and lower parts of window frame, hereafter Position 1 and Position 2 respectively (see Fig. 2) to compare and to analyze the accuracy of the TSL2561-illuminance sensor. The other data such as demonstration time, TSL2561-illuminance values, and stepper angle were real-time-recorded by Arduino and directly transferred into the memory card and serial monitor of Arduino IDE software. These recorded data were used to analyze the response time, mechanical performance as well as control system performance of the system.

Procedure for the test was commenced by emanating different illuminance values from the light sources by varying the number of the bulbs, i.e. from one to five bulb(s) on the sensors at both upper and under part of window frame. To analyze the algorithm performance, the different threshold illuminance values were set in the Arduino's program; they are, 500lux and 1000lux. Under these conditions, total of 20 test conditions were performed. During each test condition, lux-meter and angle values of motor stepper were monitored for every three minutes.

For the Mode 2 assessment, the test was conducted in the test house. Figure 6 illustrated the test configuration under Mode 2 in the test house. The shading device was installed on the west wall of the test house. The test focused on the evaluation of the windowpane movement and see the fitness of the movement with the program.

3. Results and Discussions

3.1. Sensor Accuracy

Sensor is the most important part of this system since it received the stimulus (i.e. solar radiation represented by illuminance) from the outdoors and then proceed it to the main brain (microcontroller Arduino). Therefore, the

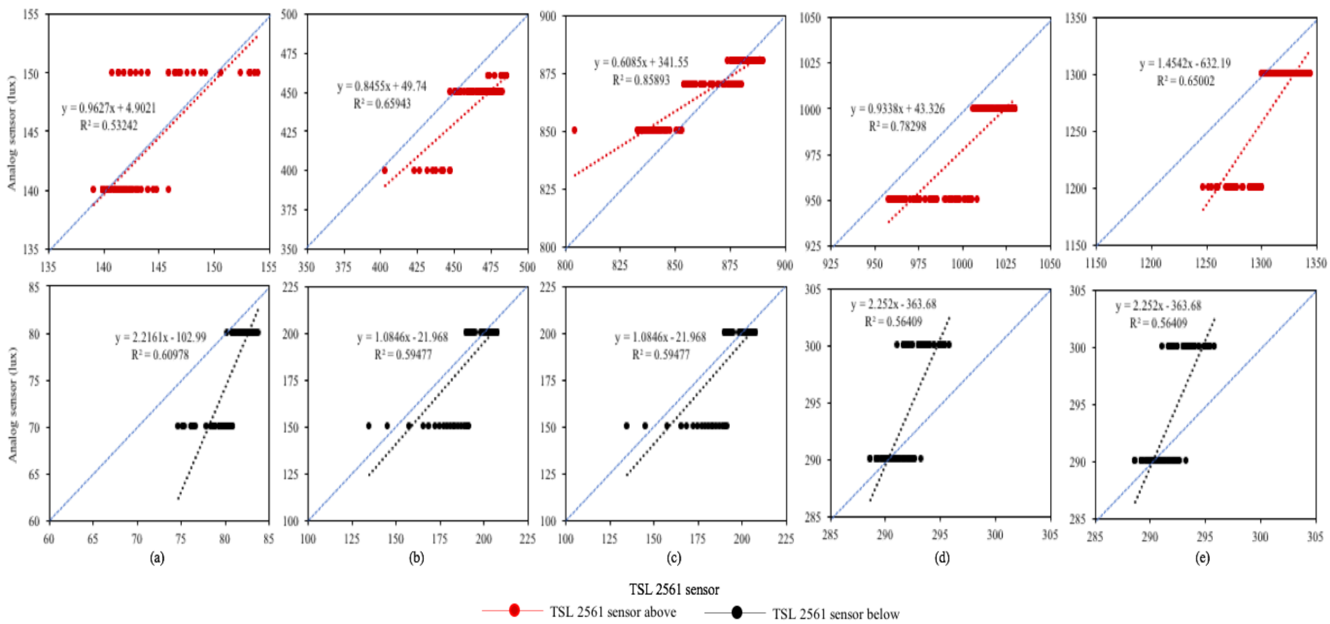

Fig. 7. Monitored data from accuracy sensor: (a) using 1 lamp; (b) 2 lamps; (c) 3 lamps; (d) 4 lamps; (e) 5 lamps.

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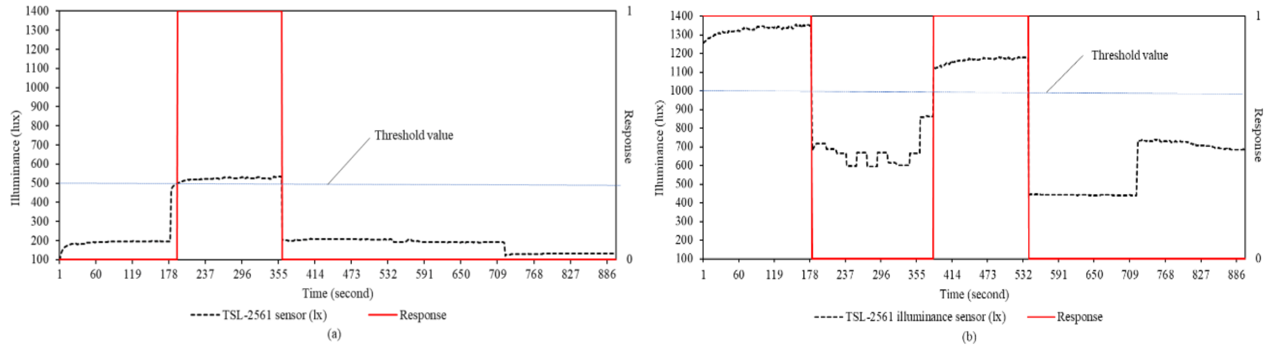

Fig. 8. Actuator response on illuminance: (a) automated shading with illuminance threshold of 500lux; (b) illuminance threshold of 1000lux.

Fig. 9. Movement of the windowpane every 15 minutes.

accuracy of the sensor is the key factor in determining the device performance. Accuracy of the sensor was assessed using statistical approach.

Figure 7 presents the illuminance values from both TSL2561-illuminance sensor and analog luxmeter under different locations of the sensors (i.e. above and below window frame, respectively). It is shown that by placing at the upper part of the window frame (i.e. Position 1), the sensor receives relatively higher illuminance values compare to that of the opposite side (i.e. Position 2). As indicated, the illuminance values at the upper side when the five light bulbs applied were recorded at from 1247.35lux to 1344.11 lux, whilst at the bottom side showed relatively lower (670.35lux - 768.59lux). The same phenomena with the significant discrepancies also could be observed when the light bulbs applied differently (i.e., four bulbs, three bulbs, etc.). These discrepancies were mostly caused by the shaded area at the bottom part and therefore it decreased the illuminance received by the sensor. It is obviously implied that Position 1 was found to be the better position for the sensor placement. It means that upper position would bring the sensor to sense the actual condition of the solar radiation rather than that at its opposite (Position 2). Despite the bias of data from the sensor at Position 2, the automated shading device maintained sending the order to the actuator (i.e., motor stepper) to move up and down continuously.

The comparison of the illuminance values between the TSL2561-illuminance sensor and the analog sensor showed that both had relatively higher correlation with the R^2 value above 0.5 (see Fig. 3). As shown, the correlations when five light bulbs applied were 0.71 and 0.79 for Positions 1 and 2, respectively. Under different light bulbs, the correlations were range from 0.53-0.86 and 0.53-0.74 for the sensors at Positions 1 and 2, respectively. From all the tests performed, the illuminance value from TSL2561-sensor were generally not significantly different compared to those of analog luxmeter with the accuracy around of 67.3% and the error of around 32.7%. A relatively large error occurred during the test most probably due to the small sensitivity of the analog luxmeter. The TSL2561-illuminance sensor has a sensitivity around of 0.1lux. It should be noted that lux-meter is an analog sensor, so that there was a possibility of error in reading the value.

3.2. Automated shading device performance

As previously described, the performance test mainly focused on the control system and the mechanical design of the test was performed to investigate the workability of the mechanical and control system. Performance test for the control system was conducted by analyzing the algorithm sequences and made sure it works accordingly. As previously discussed, in the Mode 1 the different illuminance thresholds were applied; i.e. 500 lux and 1000 lux. In both threshold modes, the on/off control was used as a control strategy. In this test, the shading device was at active state (i.e. tilt angle: 45°; actuator response: 1) when the received illuminance values exceeded the threshold values (i.e., 500 lux or 1000 lux) and it was at fully opened or off state (i.e., tilt angle: 0°; actuator response: 0) when the illuminance values did not exceed the threshold value. Figure 8ab show the actuator (i.e. motor stepper) response on the detected illuminance value at 500 lux and 1000 lux, respectively. In general, the difference threshold modes performed very well according to the control algorithm. As can be seen in Fig. 8a, the actuator at Mode 1 was at off state when the illuminance value was less than or equal to 500 lux and the actuator was at active state when the illuminance value exceeded the 500 lux. The similar response was found at 1000 lux (see Fig. 8b).

Laboratory scale test demonstrated promising performance of the proposed mechanical design for the automated shading system. In this preliminary development phase, the materials used for the windowpane (i.e. corrugated plastic sheet) supported the mechanical system. Based on the performance test results, it is evidenced that the motor stepper enabled moving the windowpane without any significant interferences and obstructions. For the purpose of mechanical test, as previously implied, the rotation angle with tilt angle 0°-90° was applied to block the solar radiation. It is also appeared that the motor stepper smoothly synchronized with the operating mechanism. The evaluation of control algorithm indicated that the windowpane rotated according the program less than 3 seconds. To increase the rotating process, the delaying time in control algorithm should be reduced. As anticipated in each process, motor stepper had a time delay; in this case the input delaying time was 1000 micro-second. Although the delaying time of motor stepper can be reduced, however it had a minimum required delaying time around 5 micro-second to work properly.

Even though the Mode 1 showed good result in mechanical movement, the windowpane movement using this mode (on/off) was redundantly on-off. Therefore, Mode 2 was developed as the next development mainly focused on the movement of motor stepper at certain angles. For the first step, this movement was designed based on the solar altitude from sun path diagram. The evaluation of the Mode 2 showed that the angle movement of the windowpane was well fit with the program input on the microcontroller. At the 17.00 for example, the program was set to move down the window at 55° and the evaluation results showed that the windowpane angle was 35° . At 18.00, the windowpane restored to its original position (Fig. 9). Nevertheless, further development is necessary particularly for the designing window to move based on the radiation received by the sensor.

3.3. Evaluation and further development

Although the shading devices worked properly during the performance test, nevertheless further development must be performed particularly on the new algorithms for the movement of the pane according to the stimulus given in actual situation. On/off control algorithm is considered no longer sufficient to response the actual thermal conditions. In order to do so, the sensor placement, determination of the step rotation range of motor stepper, and indoor thermal performance due to the automated shading devices were further investigated. As previous results, the sensor accuracy more and less depend on the surrounding condition (e.g., shaded area due to the windowpane or other components) and therefore, the challenge of sensor placement should be further evaluated under actual condition since it significantly interfering the sensor performance. From this works, it is concluded that the optimum performance obtained from the sensor located at the above the shading/window glazing area (Position 1). Moreover, for more additional sensor placements, the investigation of sensor placement in the other non-shaded areas (e.g., left or right side of window glazing area) should be further considered.

Furthermore, the optimization of control algorithm must be improved to obtain more detailed operation range of the motor stepper. The development of this range might be a great challenge since it needs to find the correlation between the received illuminance and the appropriate tilt angle of windowpane to achieve the acceptable indoor visual and thermal performance. In order to find this correlation, the performance test under actual environments will be carried out in the next phase of development.

4. Conclusions

This work presented the results of development of prototype of automated shading devices. The prototype consists of four main components, i.e. physical system, mechanical system, sensor and data acquisition system and control system. This study exemplified that the sensor and acquisition data system, mechanical system, and control system worked properly and synchronized. From the performance test results, data acquisition for illuminance value using TSL2561-illuminance sensor was relatively fast and quite reliable with accuracy was about 0.53 – 0.86 and ease to configure due to its small dimension. The placement test results implied that the optimum performance obtained when the sensor placed above the shading/window glazing area (Position 1). However, for other alternative positions, further investigation of sensor placement particularly in other non-shaded areas (e.g., left or right side of window glazing area) are necessary.

The corrugated plastic sheet was found to be suitable for the windowpane in this preliminary phase. Since it is lightweight, the motor stepper enabled rotate the pane without any problems and errors. The motor stepper also well performed with rotation time about 3 seconds. Although the rotation time can be reduced by decreasing the delaying time; the minimal delaying time of motor stepper specification must be further considered. By applying two modes control system (i.e., based on illuminance value and sun path diagram dara), the automated shading worked appropriately as the input algorithm; whether at active state or at fully open/off state. However, the control algorithm must be improved to obtain a detailed operation angle range by examining it under actual environments. The performance test not only evaluates the control system but also investigate the mechanical system, sensor and acquisition system, and the indoor thermal environments in consideration of the application of this equipment.

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