An Automated Louver with Innovative Parametrically-angled Reflective Slats: Prototyping and Validation via Using Parametric Control in Grasshopper along with Arduino board

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1 ABSTRACT

Energy-saving potential in lighting is significant in office buildings due to their primary occupancy during the daytime. This potential can be realised with an advanced daylighting system being particularly able to deliver more uniform and steadier illumination. This paper presents prototyping and experimental validation of an automated louver with parametrically-angled reflective slats, in order to reflect sunlight to evenly distributed target positions on a ceiling. The illuminated ceiling acts as a source of diffuse light to the room. The physical rotation of the automated louver is controlled parametrically using Grasshopper software together with Arduino board, motors for the motion and illuminance sensors. Validation is an essential stage to ensure the performance of such systems. Two prototypes of the proposed system with different scales are presented, 1:20 and 1:1 scaled mock-ups. The monitoring results verify the principle and aim of the proposed
design, i.e., more uniform and distributed daylight illumination, automation control method besides its practicality.

**Keywords:**
Daylighting; Automated louver; Parametrically-angled; Prototyping; Validation; Grasshopper; Arduino board

2 Introduction

Advanced daylighting systems can be exploited to engage with architecture to improve building environment and enhance buildings’ energy performance [1]. Architecture has become more vivid as it has been redefined with different descriptive features such as smart [2], green, sustainable [3], passive [4, 5], active [6], dynamic [7] and adaptive buildings [8], while all these characters are directed to the same target; comfortable, healthy and economically-viable environment. In order to achieve an energy-efficient adaptive building, innovative daylighting systems along with Building Information Modelling (BIM) technology should be vital tools to control indoor performance with responding to outdoor conditions. In the context of architectural practice, BIM and Innovative daylighting system can help to improve building energy systems for higher energy efficiency.

Daylighting systems were investigated previously in the last 30 years in combination with automatic control [9, 10] aiming to improve their performance [11-13], increase their accuracy, enhance human visual comfort and save more energy [14]. The number and kinds of worldwide publications about the automated daylighting system in the last 30 years are shown as a statistical survey in Figure 1 and Figure 2 [1-3, 15-95]. The statistical survey was accomplished by using the keywords “daylighting systems” and “automatic control” in different research engines. Meanwhile, 80% of these
Automated daylighting systems are blinds due to their feasibility and ease of use. Furthermore, up to 50% saving in lighting energy consumption can be achieved by using such automated systems in commercial buildings [96].

Innovative daylighting systems, such as light guiding systems and light transporting systems [97] have been recently improved [12, 15, 36, 98], however, potential limitations such as cost, size, performance and feasibility are still critical obstacles [36]. Meanwhile, efforts have been moving forward to optimise the use of daylight [28, 99, 100]. Automated daylighting systems can save up 50% of electrical energy comparing to 20% of the stationary systems at their best performance [9, 14, 101]; however, the efficiency of these automated systems are still limited due to their control difficulties and users’ preferences [22]. Recently, the parametric design has been utilized to provide better control, more accuracy and solve complex relations simultaneously [85].

![Figure 1: Annual number of publications on automated daylighting systems](image1)

![Figure 2: Count of publications of each type on automated daylighting systems](image2)
As a parametric control method, Grasshopper was particularly utilised in previous studies to adjust the direction of mirrored surfaces for better daylight distribution inside the room [6, 102, 103]. For example, a study investigated the rotation control of a reflective lightshelf according to the sunlight incident angle to improve daylighting performance in an office room in New York [90]. Meanwhile, Microcontrollers within Arduino board have been utilised previously in several studies as a physical control method to improve the energy efficiency and comfort conditions. However, the accuracy mechanism of the automation in some cases were highly complicated which needs regular maintenance [1, 104, 105]. For instance, In Al-Bahar Towers in Abu Dhabi, a parametric façade inspired from the Mashrabiya and natural adaptive systems which can respond to the solar changes to control the daylight penetration and reduce the heat gain. The mechanism of the façade was automated parametrically using 1,049 Mashrabiya unit for each tower. The fabrication and manufacturing were challenging in terms of automation complexity, high cost and maintenance. Although, the façade system succeeded to reduce significant amount of heat gain, however, regarding the automation, each Mashrabiya unit can unfold at only two position which considered not satisfactory for accuracy control. This showed extreme difference in the results when the units are fully folded or fully unfolded, which could be a limitation with solar control [106].

The current study therefore focuses on high accuracy and simple control, via using an automated louver based on parametrically-angled reflective slats which can constantly respond to the sun movement wherever the sun moves [99]. Meanwhile, using simple microcontroller by implementing parametric control in mock-up prototypes for validation. The automated louver has been
exploited to provide evenly distributed daylight inside the room with a simple rotation control [107]. The study aims to validate the performance of the proposed daylighting system in 1:20 and 1:1 mock-ups study and also the application of microcontrollers in the prototypes as a simple control method.

3 Methodology

The method of this system is based on redirecting the incident sunlight onto the ceiling, and then the ceiling works as a source of diffuse light to the room via using parametric control. The slats are parametrically angled, where every single slat has a specific rotation angle, aiming to reflect the light beam to a fixed target on the ceiling. The slats can parametrically respond to the sun movement in order to keep these targets fixed on the ceiling [99] as shown in Figure 3 (a), (b).

![Figure 3](image.png)

*Figure 3: Parametrically-angled reflective slats, the light is reflected to fixed targets during the sun movement.*

The parametric software Grasshopper plays an important role to calculate the variables of the system simultaneously, i.e. sun movement, slats rotation and distance between targets. Moreover, time and date should be prior specified to obtain solar directions of this location. The study aims to validate the simulation results obtained from the digital model with the outcome recorded from the physical model. The performance of this system has been
investigated previously and proved that it could provide steady and distributed daylight inside an office room in addition to achieving up to 50% of electrical energy saving throughout the year [101].

The current study investigates the automation control method for such a system to demonstrate and validate its practicality. The flowchart of the validation process starts with specifying the prototype location by inserting EPW file in the “Ladybug” component; likewise, time and date inserted as an input data in Grasshopper. Then, the input data should be calculated via Grasshopper’s formula to obtain the slats’ rotation values. Thereafter, the values of the angles are sent to Arduino board as a microcontroller via a specific plugin known as “Firefly”. Finally, the Arduino board send signals to the servo-motors with the specified angles which should accordingly rotate the slats, see Figure 4.

![Flowchart of the validation process](image)

Figure 4: Conceptual diagram showing the process from importing data to prototyping.

### 4 Experimental study of the 1:20 mock-up

A scaled prototype has been created to validate the results obtained from the computer simulation of the automated louver. The prototype was built in a scale of 1:20 for an office room of 8m depth, 4m height and 12m width. The prototype was assembled of 3mm plywood with a movable ceiling. The
south side was fitted with an automated louver system. The walls and ceiling were matt white painted to give a typical 80% reflectivity, while the floor was covered with standard grey carpet. A side circular access opening was created to take a snapshot of the interior with a wireless controlled camera, see Figure 5. The test was carried out at the University of Nottingham in May, July and August. Times were selected in the middle of the day between 10 am and 3 pm. The validation method of this study is based on three main parts; the physical part which contains the hardware and all physical controllers, the digital part which contains the software and all digital controllers, and the measurement part which contains the sensors and the measurement devices.

4.1 The physical parts

4.1.1 Micro Servo Motor to control the rotation of the Louver system

The automated louver consists of parametrically-angled reflective slats which can rotate according to the solar altitudes. Particularly, all slats are parametrically-angled in order to target the wider area of the ceiling, but their rotation angles can be the same for a simple automation [8, 107]. The automated louver was installed at the upper part of the window as seen in Figure 5. Rotation of the slats was actuated by micro-servo motors to control of the motion of the slats. The micro-servo motor accuracy is 1 degree, and
it can rotate up to 180° in one direction, brand “9g Micro Servo Motor (4.8V)”. As mentioned above, a set of slats can be actuated with a single micro-servo motor theoretically, however, for better balance, two micro-servo motors were fixed at the two ends of each slat to control its rotation. The signal for a required rotation degree is delivered from an electronic board known as Arduino board.

4.1.2 Arduino board

Arduino is a well-known electronic platform based on easy-to-use hardware and software, and it has been utilized in many fields due to its distinctive capabilities and low cost. It is a microcontroller based on Integrated Circuits and has been particularly exploited to control micro servo motors, stepper motors and robotic kits. Arduino can be therefore used as a mediator between the digital simulation and the real model. Arduino MEGA 2560 was used with 1:20 mock-up due to its capability to control several parameters [108]. It has 54 digital binary codes (1/0) pins and 16 analogous inputs/outputs [109]. In the current experiment, Arduino MEGA 2560 was attached to an expansion shield known as “DFRobot Mega” as shown in Figure 6, which facilitates a connection to the Actuators. It is utilized to take all the information and data from the computer and deliver them to the actuators via an algorithmic software called Firefly.

Figure 6: The expansion shield is attached to the Arduino MEGA 2560 board to facilitate its connections
4.2 The digital tools

4.2.1 Firefly software

The connection between the PC and the Arduino board is a physical connection using USP connection. Behind the computer screen, this connection is translated to Grasshopper and Firefly as shown in Figure 7. Firefly is open-source software that can be downloaded as a plugin in Grasshopper to serve as a bridge between Grasshopper and the Arduino microcontroller [110]. The interface components of Firefly is a translation of the Arduino board’s input/output pins [1], see Figure 7. It allows the components of Grasshopper to open a connection to the serial port, read the rotation angles in Grasshopper, and deliver it out into Arduino. In general, Arduino must be defined to a PC in order to send and receive data from Firefly via a novel communication protocol called "Firefly Firmata" [111].

4.2.2 Grasshopper

Grasshopper is a well-known parametric software developed to generate NURBS drawings and complex geometries with different parameters [85]. Grasshopper is based on Rhinoceros 3D developed as a graphical algorithmic editor while it can control several parameters simultaneously under particular definitions connected in a formula. This formula defines the model parameters in a flexible way which can provide substantial opportunity to manipulate with
the whole model [112]. Grasshopper interface is capable of inserting different plugins with specific scripts among its components, such as “Firefly” which was discussed earlier. Likewise, “Honeybee and Ladybug” can be added to Grasshopper as plugins while they work as an engine to communicate with the well-known building simulation software Radiance, DAYSIM and EnergyPlus [113]. Ladybug was used as a gate to provide comprehensive weather data of any selected region, by directly importing the EPW file of the chosen region to Ladybug, then, the weather data of this location should be available and intuitively influence on the model in Grasshopper.

4.3 The measurement tools

Two photosensors were used inside the prototype to detect the illuminance level over the floor; the sensor height is 3 cm from the floor (equivalent to 60 cm at full scale); the first one was set 5 cm away from the window, and the other sensor set 5 cm away from the back wall, see Figure 8.

Both sensors were connected to two lux meters (HAGNER LUXMETER, MODEL E2-X), as shown in Figure 8 to display the illuminance value. It should bear in mind that the test points in Grasshopper represent the photosensors in the prototype.
4.4 Limitations of the experimental design

4.4.1 Fixed shade

The slats were covered with mirrored film with 75% reflectivity. Each reflective slat may have its edge attached to a fixed black shade slat [101] which absorbs downward reflected or leaked light to avoid any potential glare near the window [107]. However, due to the small scale and controlling difficulties; a single shading plate was fixed directly under the lowest reflective slat instead of several fixed slats, which should do the same function as shown in Figure 9. The current study focused only on the influence of the reflected sunlight to the deep room regardless the intensity level of the daylight, aiming to validate the performance of the automated louver. The bottom window accordingly was also ignored in this test and replaced with an opaque surface.

![Daylight coverage 90% with a shading plate](image1)

![Daylight coverage 92% with the shade slats](image2)

*Figure 9: A single shading plate (on the left) can do the same function as the shade slats (on the right) in addition to the Parametrically-angled reflective slats. Note: the simulation has occurred for the 1:20 scaled prototype.*
4.4.2 Number and size of the slats

The prototyping aims to validate the automated louver, which can rotate according to the sunlight altitudes via using parametric control. As a full-scale model, number of slats in the simulation were set to 10, the dimensions of a single slat unit were supposed to be 12m length, 15cm width and 3mm thickness. However, when rescaling these parameters to match the prototype size 1:20, the results were inaccurate due to its small size. Rescaling and cutting a mirrored stainless steel to 7mm width and 60cm length influenced badly on its shape properties, which became like a spiral shape, in addition to its surface irregular surface. Moreover, it was difficult to fix and rotate a fragile slat along the 60cm length, which resulted in a zigzag reflection over the ceiling, see Figure 10.

![Stainless steel slats](image)

Figure 10: The initial setting of the prototype with 10 stainless steel slats. Interior shot (left), exterior shot (right).

To improve the accuracy control; number of slats was changed from 10 to 3 and the dimension of each slat was changed to be 3 cm wide (equivalent to 60cm in the full scale) and 2 mm thick with the same length 60 cm. Polished aluminium slats (with 90% specularity) were replaced with the stainless steel slats due to their strength and lightweight, see Figure 10. It should be considered that the number and size modifications of the slats would not influence the function of daylighting performance and its validation as long
as the settings in the simulation are adjusted accordingly. Both parameters were examined in the simulation in order to produce the same result and performance. By examining 10 slats with 0.7cm width in a simulation, the daylight coverage achieved 92% on the 21st of June at 12 p.m. Meanwhile, by changing the number of slats to 3 with a specific equivalent distance (2.7 cm) [99] between them and 3 cm width; the daylight coverage was almost the same at 92%, see Figure 11. The percentage value here represents the percentage area with the daylight illuminance between 300-500 lx which was chosen according to CIE standards [114].

![Daylight analysis: Between 300 & 500 lux = 92%
Time and date, 12.07Thursday, June 21st 2018
Min & Max range: 250.0 To 458.0](image1)

![Daylight analysis: Between 300 & 500 lux = 92%
Time and date, 12.07Thursday, June 21st 2018
Min & Max range: 299.0 To 514.0](image2)

Daylight coverage 92% with 10 slats

Daylight coverage 92% with 3 slats

*Figure 11: Daylight coverage for 10 and 3 reflective slats, respectively. Note: the simulation has occurred for the 1:20 scaled prototype.*

### 4.5 Sky conditions

Three sky conditions were investigated, clear sky with sun, intermediate sky and overcast sky [115]. The analysis of Daylight hours for the selected location reveals that the sky is clear, intermediate and overcast during 17%, 47% and 34% of the year respectively, based on the criteria in Table 1 [116]. For daylight analysis, the study uses forward raytracing based on Radiance software, which can analyse illuminance distribution inside the room.
### Table 1: Sky types

<table>
<thead>
<tr>
<th>CIE sky type</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>Direct normal irradiance is more than 200% of diffuse horizontal</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Direct normal is between 5% and 200% of diffuse horizontal</td>
</tr>
<tr>
<td>Overcast</td>
<td>Direct normal is less than 5% of diffuse horizontal</td>
</tr>
</tbody>
</table>

## 5 Monitoring of the 1:20 mock-up and validation of design

Firstly, the illuminance levels were monitored in random days to evaluate the system’s performance in a long term, then the simulation results have been validated with the prototype results by choosing specific days with different sky conditions.

### 5.1 Monitoring the illuminance levels

The illuminance monitoring has been occurred inside the prototype in May, July and August on different days with different sky conditions between 10 a.m. and 3 p.m. by using the back and front sensors, see Figure 12, Figure 13 and Figure 14. A predominant illuminance level can be seen between 300~500 lx. Sky conditions at this range were varying between intermediate and overcast sky. Meanwhile, the illuminance levels ranging between 600~1500 lx is relatively higher due to the influence of direct solar radiation.

In terms of uniformity of daylight distribution, the automated louver provided a satisfactory performance which met the design expectation. This uniformity can be seen in the difference between the back and front sensors which is relatively convergent. Although the recommended illuminance level for visual comfort in office buildings should be between 300~500 lx according to CIE standards [114, 117, 118], a previous study [119] claims that lighting level between 100~2000 lx can meet human visual comfort based on occupants’ survey. Therefore, if the illuminance range 100~2000 lx was considered as an acceptable range for the occupants, the proposed
automated louver can be considered as a promising application in office buildings to save electrical lighting energy.

![Figure 12: Daylight illuminance monitoring in May on random days between 12 pm and 2 pm](image1)

![Figure 13: Daylight illuminance monitoring in July on random days between 10:30 am and 3 pm](image2)
5.2 Design validation of the automated parametric louver with both illuminance values and HDRI image

The experiment was carried out to validate the results of the prototype with the simulation results in Grasshopper by comparing the real illuminance maps with the rendered maps in the simulation. It should bear in mind that both simulation and experiment outputs were measured locally at the same time zone. The input used in the simulation was EPW weather file based on CIE sky type. The real illuminance maps of the test were captured using action camera inside the prototype, then, an effect of "light-scale gradient" was applied on the maps to produce the HDRI illuminance maps as shown in Table 2.

Meanwhile, HDRI maps in the simulation were generated in Grasshopper using "Honeybee False Color" component, valued in luminance cd/m². The luminance performance of the daylight can be seen in the bluish colours in the maps, where, the blue colour means more intensity and the purple colour means lower luminance levels. Luminance levels in the prototype were ranging between 50~2200 cd/m² [120-122].
<table>
<thead>
<tr>
<th>Date &amp; time</th>
<th>Sky condition</th>
<th>Measurements</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>31-7-2018 13:00</td>
<td>Sunny</td>
<td>1385 / 1430</td>
<td>1140 / 1450</td>
</tr>
<tr>
<td>31-8-2018 13:00</td>
<td>Sunny</td>
<td>1410 / 1460</td>
<td>1393 / 1426</td>
</tr>
<tr>
<td>7-8-2018 13:00</td>
<td>Intermediate with sun</td>
<td>850 / 1150</td>
<td>974 / 1211</td>
</tr>
<tr>
<td>31-8-2018 15:00</td>
<td>Intermediate with sun</td>
<td>900 / 1100</td>
<td>765 / 938</td>
</tr>
<tr>
<td>9-8-2018 12:00</td>
<td>Overcast</td>
<td>330 / 300</td>
<td>382 / 292</td>
</tr>
<tr>
<td>9-8-2018 13:00</td>
<td>Overcast</td>
<td>570 / 550</td>
<td>325 / 411</td>
</tr>
</tbody>
</table>

**Table 2:** A comparison of HDRI maps between the measurement in the prototype and the simulation.

**Measurements:**
- HDRI real map from the prototype
- B/F Sensors values

**Simulation:**
- HDRI fish eye false colour from Grasshopper
- B/F Points equivalent to the sensors
- Daylight illuminance analysis map from Grasshopper (top view)

**Case 1**

**Case 2**

**Case 3**

**Case 4**

**Case 5**

**Case 6**
In the experiment, two methods have been used to record the measurements by using Grasshopper, the first one measured the maximum and minimum illuminance levels inside the room, while, the second one measured specific points inside the room. However, the latter method has been chosen for the study, which represents two test points equivalent to the location of the sensor which should be more reliable.

In Table 2, for sunny conditions, the recorded values at the back and front sensors in the prototype were 1385 lx as a minimum value and 1460 lx as a maximum value, respectively. For overcast sky condition, the illuminance values were ranging between 300 – 570 lx, which is considered satisfactory. The reason for such balance reveals beyond the type of daylight coming from the skydome as a contribution of diffuse radiation.

In Case 1 the influence of direct solar radiation concentrated in the area of the ceiling near to the window which accordingly increases the illumination of the room. In this case, the simulation gave 1140 lx at the back and 1450 lx at the front, which was relatively close to the experimentally recorded 1385 lx at the back room and 1430 at the front. For the intermediate sky condition in Case 3, the simulation recorded; 974 lx back and 1211 lx front, which was relatively equivalent to the sensors’ records; 850 lx and 1150 lx back and front, respectively. An illuminance difference can be noticed between two sky conditions Case 4 and Case 1 due to the influence of diffuse light from the skydome more than direct sunlight, according to Table 1. In Cases 5 & 6 due to the overcast sky condition, the slats can reflect only the diffuse light from the skydome, which accordingly resulted in a moderate illuminance distribution inside the room. Cases 2 & 4 were relatively similar to Cases 1 & 3 respectively due to their similar conditions. Overall, the values resulted
from the sensors were relatively close to the values from the simulation, which should be a promising outcome for such a validation study.

The white matt surfaces of the walls and ceiling were playing a vital role in the daylight illuminance distribution inside the room due to their diffuse characteristic; mainly when daylight is reflected onto the ceiling, it acts as a source of light to the room. For instance, the nearby part of the ceiling near to the window is responsible to lit approximately two-third part of the room, while, the end corner of the ceiling is responsible to lit approximately one-third part of the deep part of the room [123], see Table 2, top view maps. The optimisation method is to achieve a balance between these two illuminated areas in order to keep within an accepted range [107]. Direct solar radiation and diffuse horizontal radiation are changing all over the year and varies based on the territory type and altitude changes [124, 125], which also influence on the illuminance level inside the room.

6 Prototyping of a 1:1 mock-up for a field test

A prototype with a scale of 1:1 has been fabricated for a field test to verify the onsite performance of the parametric louver system. The mock-up frame was made of acrylic using a laser cut. The mock-up was assembled in a square shape 80*80 cm height and width as a window frame. Two sides of the frame have been perforated at 29 vertical apertures with 22 cm equidistant between each aperture and Ø 0.5 cm for each. These 29 apertures were used as guide for Ø 0.5 cm aluminium rods, which used as a single rotation guide axis for the slats. One side of these rods was attached with 29 gears controlled by "rack and pinion" system, whereas, all the slats have the same rotation magnitude, but with a proper angle for each, see Figure 15. Therefore, "rack and pinion" as an accurate controller system can rotate all the slats
simultaneously with a prior specified rotational angle for each slat. Rack and pinion movements are controlled by one stepper motor mounted at the top of the acrylic frame. The stepper motor is controlled by Arduino Uno based on Firefly as a plugin in Grasshopper [110].

It should be considered that the controlling process of this 1:1 mock-up is similar to the 1:20 mock-up, however, in this system only one stepper motor was used (controlled by Arduino Uno), instead of using several motors. Both methods are based on Grasshopper, Firefly and Arduino board control.

6.1 Field testing of the 1:1 mock-up

Firstly, the mock-up has been tested in a lecture room oriented to the southwest, in order to calibrate the measurements tools and verify the mock-up control. This test room was 8 m length and 6 m depth and 2.7 m height. The mock-up was mounted at a lower level at 1 m height, while, the lower part was just a simple wall. The test has been occurred at 2 p.m. in a clear sky condition with direct sunlight, on the 21st of May, see Figure 16.

The illuminance has been tested in two conditions; the first condition by using normal Venetian blinds were the slats are horizontally deployed, while
the second condition by using the parametric louver. The measurements have been taken using the same two sensors and lux meters of the 1:20 mock-up. The sensors have been located in 1.5 and 3 m away from the wall, at the front desk along under the illuminated patch, where, the desk is 0.75 height from the floor. For the (common blinds) the sensors recorded 87 lx and 109 lx respectively, however, for the (parametric louver) the sensors recorded 313 lx and 308 lx respectively, which meets the recommended illuminance range 300~500 lx. We have to put in consideration that the illuminated patch width is relatively small, which potentially produces lower intensity than expected. However, if it is applied on a broader scale, the contribution of the reflected light can probably increase.

6.2 Verification of the 1:1 mock-up

A validation study has been made for the 1:1 mock-up, in a south-oriented meeting room. The mock-up was mounted to the upper part of the window at 2.2 m height. The lower part was covered with black fabric, while, the area near to the window has been ignored in this study. The room is 10 m length and 7.3 m depth, and 3.8 m height. The test has been made between 11 a.m. and 1 p.m. on selected sunny days in May, June, July, August and September. The test time was limited between 11 a.m. and 1 p.m. due to the small size of the mock-up, while, the illuminated patch decreases before and after these
times and the contribution of the reflected light becomes lower. Meanwhile, the test was occurred to validate the efficiency of the louvre system in its optimum performance.

Table 3: A comparison between parametric louver mock-up and common blinds conditions using three different sensors in a meeting room, from May to August on selected sunny days

<table>
<thead>
<tr>
<th>Time</th>
<th>Horizontal illuminance</th>
<th>Vertical illuminance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Common blinds</td>
<td>Parametric louver</td>
</tr>
<tr>
<td></td>
<td>at 1.2 m</td>
<td>at 2.2 m</td>
</tr>
<tr>
<td>12:30 p.m.</td>
<td>83700</td>
<td>61500</td>
</tr>
<tr>
<td></td>
<td>165 lx</td>
<td>198 lx</td>
</tr>
<tr>
<td>1 p.m.</td>
<td>70500</td>
<td>43400</td>
</tr>
<tr>
<td></td>
<td>145 lx</td>
<td>189 lx</td>
</tr>
<tr>
<td>1:30 p.m.</td>
<td>65810</td>
<td>36900</td>
</tr>
<tr>
<td></td>
<td>64 lx</td>
<td>123 lx</td>
</tr>
</tbody>
</table>

The sensors have been located in three positions under the illuminated patch at 1.2, 2.2, and 3.4 m away from the wall facing the window. The test has been occurred using off/on states; therefore, six figures have been recorded for each time; also the horizontal and vertical illuminance for the solar radiation has been recorded at each time, see Table 3.
The results in the “off state” in Figure 17 reveal a noticeable variation among the illuminance values which slightly increased towards the window; moreover, the illuminance levels at 1.2 m were giving lower values than the required threshold level 300 lx, which considered inappropriate for human visual comfort [126]. The required illuminance range based on CIE standard [122] should be within the range 300 ~ 500 lx as highlighted in green in Figure 17. Promisingly, in the “on” state, as shown in Figure 18, variation between the illuminance values is relatively reasonable within the range 300~600 lx, which considered above the required threshold level. Moreover, the difference between the illuminance values in the “On state” ranges within <>100 lx, which considered relatively steady compared to the “off state”.

Figure 17: Illuminance levels – common blinds condition.
Figure 18: Illuminance level – Parametric louver.

7 Discussion

This validation study was carried out for two main aims, to validate the system’s performance and demonstrate its practicality as a control method. The first aim focuses on the capability to distribute the daylight inside the room with respond to the sun movement. Compared to static system which cannot provide uniform daylight inside the room, even the automated shading system which can only protect from direct sunlight. However, the parametric louver system can successfully achieve both functions by providing steady uniform daylight and simultaneously protect from direct sunlight. The second aim focuses on the ability to execute and control such a system by using small actuators and simple electronic board. It should bear in mind that potential glare has been dramatically mitigated due to the high number and reduced size of the slats in the 1:1 experiment which helped to decrease the gaps between the slats (compared to the 1:20 mock-up). Moreover, redirection of the light luminance plays an important role in reducing potential glare as well. In Table 3, the reflected light on the ceiling works as luminance
diffuse light to the room. However, a concentrated spark light can be seen on the wall at the edge of the room which may cause some glare. The reason for the emergence of this spark light is that the parametric louver was designed to cover 8 m depth room, while the depth of our experimental room is only 7.3 m which causes the intense of this light.

It should be considered that the proposed parametric louver is designed to be mounted at the upper part of the window which means that the view out through the window will not be blocked, while the purpose of this system is to redirect and enhance the daylight inside the deep-plan room. Additionally, this shading system works in full performance with a south and south west oriented room with direct sunlight compared to other orientations.

Regarding the 1:1 mock-up, the limited size of the prototype reduces the opportunity of maximum daylight harvesting, which can probably yield better performance with a full-scale system. Generally, the results revealed that the parametric louvre system (2.5 cm width) with a simple automation control can significantly provide 8-meter deep room with constant and steady daylight within an acceptable range, which can achieve visual comfort and save electrical energy.

8 Comparison

Daylighting systems have different shapes, settings and efficiencies; however, they may differ in installation method and outcome performance based on their designed function. The next table showing a comparison between previous daylighting systems which are similar to the function of the parametric louver system, as shown in Table 4.
Table 4: A comparison between the previous daylighting systems

<table>
<thead>
<tr>
<th>Daylighting system</th>
<th>Shape</th>
<th>Installation</th>
<th>Description</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric louver</td>
<td>Mounted at the upper part of a wall window</td>
<td>An automated slats which can respond to the sun movement.</td>
<td>Can save up to 50% of electrical energy. Can provide uniform and steady daylight inside the room within 300~500 lx</td>
<td></td>
</tr>
<tr>
<td>Lamella heliostats</td>
<td>Installed at the roof or skylight of a building</td>
<td>A light guiding device can be controlled to redirect the sunlight into the interior of a building.</td>
<td>The light can be guided far into deep courtyards or light wells. Increased daylight availability in deep spaces</td>
<td></td>
</tr>
<tr>
<td>Light shelves</td>
<td>Installed at the upper part of a wall window</td>
<td>A static horizontal reflective plate which can redirect the sunlight into the deep room</td>
<td>Can provide uniform distributed daylight inside a deep room</td>
<td></td>
</tr>
<tr>
<td>Optical louver system</td>
<td>Mounted at the upper part of a wall window</td>
<td>A static louver system which can redirect the sunlight inside the room</td>
<td>Can provide uniform diffused light inside the room</td>
<td></td>
</tr>
<tr>
<td>Sundolier</td>
<td>Installed at the roof of a building with a predesigned structure.</td>
<td>A light collector of 0.6 m diameter, which collects daylight by using a set of mirrors that can track and concentrate sunlight.</td>
<td>The collected daylight is distributed to indoor areas using unique in-room fixtures. The Sundolier can deliver up to 100,000 lm of light.</td>
<td></td>
</tr>
</tbody>
</table>

9 Conclusions

This article investigates an automated louver system which can respond to the sun movement based on parametric control and validated via using actuators for the rotation control with simple Arduino board connected. The system can provide uniformly distributed illuminance inside the room within an acceptable range 300~500 lx for human visual comfort, which can be used
as an alternative to electrical lighting. The automated louver system with parametrically-angled reflective slats has been introduced in this study as a prototyping implementation for validation purpose.

The validation process started with Grasshopper as a parametric modelling software and ending with the final physical prototype. Validation is a crucial step to assess the performance of the proposed system. The test results of the 1:20 mock-up indicated that the proposed parametric louver could provide a relatively uniform distribution of daylight illuminance within a range 1450~1140 lx, 1211~785 lx and 292~411 lx for sunny, intermediate and cloudy sky conditions, respectively. The outcome results of the 1:1 prototype indicated that the parametric louver can provide steady and uniform daylight within the illuminance range 600~305 lx compared to a traditional blind which resulted unsteady illuminance range 785~171 lx.

Mainly, this study investigated this validation process thoroughly by using a mediator known as Arduino board between the prototype and Grasshopper software. Different kinds of tools can be connected to the Arduino such as sensors, monitors, micro-servo motors, stepper motor and actuators based on the needed role. Overall, with a simple and accurate automation, the simulation outcomes were promisingly close to the sensors’ values in the 1:20 prototype within a reasonable difference. Moreover, the 1:1 prototype succeeded to provide uniformly distributed daylight, which can be considered as an efficient daylighting system.

A future study will focus on using advanced windows with the automated louver to control the steadiness of the daylight.
10 Acknowledgements

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