AN OPEN-LOOP LIGHT CONTROL SYSTEM FOR DAYLIGHT-PIPE (DLP) INTEGRATED LED LIGHTING SYSTEM

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SUBMITTED IN PARTIAL FULFILLMENT OF

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SUBMITTED BY

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RECOMMENDATION CERTIFICATE

This is to certify that the thesis entitled **"AN OPEN-LOOP LIGHT CONTROL SYSTEM FOR DAYLIGHT-PIPE (DLP) INTEGRATED LED LIGHTING SYSTEM"** submitted by **SUBRATA PAIN** (Exam Roll No. **M4ILN19012**, Registration No. **107946 OF 2009-2010**) of this University in partial fulfillment of requirements for the award of Degree of Master of Engineering in Illumination Engineering, Department of Electrical Engineering, is a bonafide record of the work carried out by him under our guidance and supervision.

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FINAL EXAMINATION FOR EVALUATION OF THESIS

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of my Master of Engineering in Illumination Engineering studies.

All information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

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1. INTRODUCTION

The Tubular Light Guidance Systems (TDGS) or Daylight Pipes (DLP) are considered as the most successful and accepted method for modern daylighting applications. They redirect sunlight into core areas of deep-plan buildings. With the advance in LED technology, the need for reliable integration between daylight pipe output and artificial LED lighting has increased. Since the **light output of most basic design of daylight pipes is almost linearly related to external light level**, the artificial lights can be easily controlled, to get a certain/constant light output in the interior task area.

The output of modern commercially available LED's can be controlled with respective dimmable drivers available in market. Some of the available dimmable drivers need a phase-controlled AC supply voltage, according to which the LED light output is varied.

In this work, **an automated, real-time open-loop control system has been developed, which senses the external daylight level, and according to that, generates the phase-controlled AC supply needed for the dimmable driver**. This system operates automatically, without any human intervention. System measures the external light level periodically, and adjusts the artificial light output, to provide a fixed amount of light level in the task area of interior space.

The dimmable driver and LED luminiare that has been used here is a product of SYSKA LED. Although the control system has been tested only for this pair of LED and driver, the application of overall system can be used and extended to any other similar products, with minor changes, depending upon the product-specific light output characteristics.

- In section 2, the previous studies related to different daylighting system and daylight pipe has been discussed. Also strategies related to control and integration of daylight systems and artificial light has been studied.
- Section 3 involves the detailed discussion on the development and fabrication of the system, with the underlying theory. The detailed structure to study the DLP characteristics has been covered there.
- In section 4, the performance of the developed system has been evaluated based on experimental results.

1.1 Scope of the work

The present work involves the development of real-time automated control system for LED lamp with dimmable driver. The proposed control system adjusts the dimming level of LED's, according to the external daylight availability, periodically and without any manual input. The system basically employs an open-loop control strategy and dedicated for daylight integration with artificial LED lighting system.

The present work also targets to study the photometric behavior/performance of DLP installed in our laboratory.

1.2 Objective of the Work

The main purpose of the work is to develop an automated, real-time open-loop control system has been developed, which senses the external daylight level, and according to that, generates the phase-controlled AC supply needed for the dimmable driver. The objective towards the final completion of the work involves –

I. Study of photometric performance of Daylight Pipes.
II. Development and Fabrication of real-time control system for daylight integration with LED lamp.
III. Study of light output characteristics with variation of RMS supply voltage of a commercially available LED and dimmable driver system, developed by SYSKA.
IV. Performance study of the proposed system with simulated daylight variation.

1.3 Steps of Execution

The steps of execution of entire experimental work can be categorized into some distinct steps. These steps are briefly mentioned below-

I. Different daylighting systems and integration of daylight with artificial lighting was studied
II. Experimental set-up required to study the photometric performance of DLP, was developed and daylight data were collected.
III. Particular microcontroller board (Arduino Mega 2560), which is appropriate for the entire work, was selected.
IV. External daylight sensor, which is compatible with said microcontroller unit, was chosen. The sensor was integrated with Arduino and its performance was tested.
V. The control logic to generate the PWM pulse for phase-controlling mechanism was developed.

VI. The supply phase-controlling mechanism was developed .The control logic and phase controlling components were fabricated and tested stage by stage.
VII. These systems were integrated with LED and its light output behavior, with change in supply voltage, was tested.
VIII. The overall control system was tested under a simulated daylight environment and its performance was studied.

2. LITERATURE REVIEW

2.1 Different daylighting systems

Due to intense need of power saving and aesthetical considerations, the use of daylighting is a mandatory option for building management systems. Different types of daylighting systems has been developed and studied in last 30 years or so. From an illumination and architectural design perspective, firstly the designer needs to find the most appropriate daylighting option for a particular building/particular room or premises. Now the key parameters for choosing a system/combination of systems are:

- Site daylighting conditions—latitude, cloudiness, obstructions
- Daylighting objectives
- Daylighting strategies implied in the architectural design
- Window scheme and function
- Energy and peak power reduction objectives
- Operational constraints—fixed/operable, maintenance considerations
- Integration constraints—architectural/construction integration
- Economic constraints

Also the designer needs to fix the major objectives to apply a daylighting system:

- redirecting daylight to under-lit zones
- improving daylighting for task illumination
- improving visual comfort, glare control
- Achieving solar shading, thermal control.

To compare merits and demerits of different systems different types of studies has been done globally in last three decades. Among those, some are scale-model experiments under simulated light conditions while others are full-scale test rooms under real sky conditions at different locations around the world.
Because experimental test rooms and conditions differ significantly from site to site, the generality of these experiments is low, though the face-validity is high. Clearly scale-model experiment studies have higher generality, but low face-validity. Keeping all these considerations in mind, some most common daylighting systems are discussed in next portion.

A. Light Shelves :

A light shelf is a daylighting system that introduces external natural light into the building interiors by reflecting the light from the light shelf's reflector and the indoor ceiling surface (Figure 2.1). Also, it improves the problems of glare or uniformity imbalance by blocking the direct entry of external natural light into the interior space. The design variables for determining the performance of a light shelf include the height, width, angle, and material of the light shelf; appropriate variable control is required to maximize the performance of the light shelf.

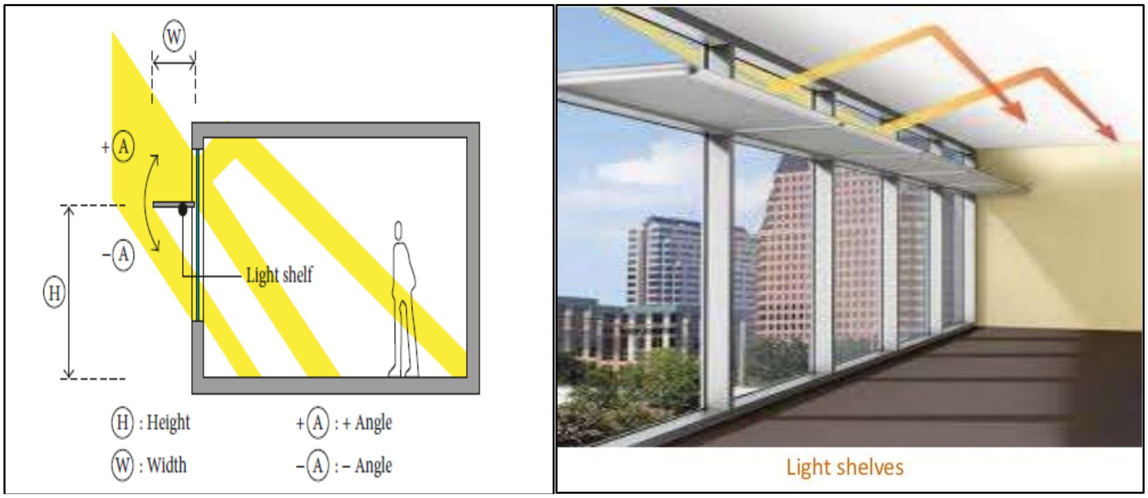


Figure 2.1: Variable (angle) light shelves (Left) and light shelves with window system (Right)

Considering the light shelves as an important daylighting solution, numerous studies has been done to design, improve performance and automatic control of light shelves. After 2015, the use of diffused reflection [1] and width-variable reflectors [2] has been considered and experimented to improve the uniformity and light gain and thus overall performance of light shelves. Both these studies include the automatic control of the proposed systems respectively.

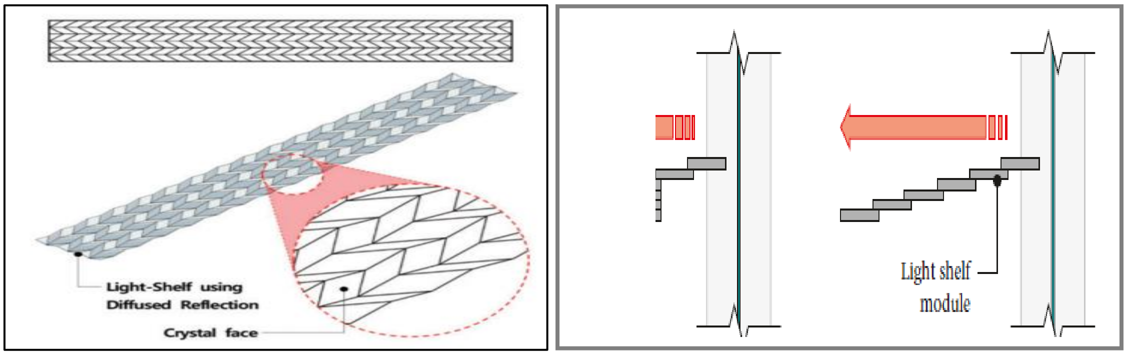


Figure 2.2: Crystal face and enlarged view of light-shelf using diffused reflection (Left) and Schematic of a light shelf with a width-adjustable reflector (Right)

B. Louvers and Blind Systems

Louvers and blinds are used in many architectural designs, mainly for solar shading, to protect against glare and to redirect daylight .They are composed of multiple horizontal, vertical, or sloping slats, and are placed on the exterior or interior of a window or skylight, or between two panes of glass. Louvers are generally situated on the exterior of the facade; blinds are fitted inside or between glazings. Depending on slat angle, louvers and blinds partly or completely obstruct directional view to the outside.

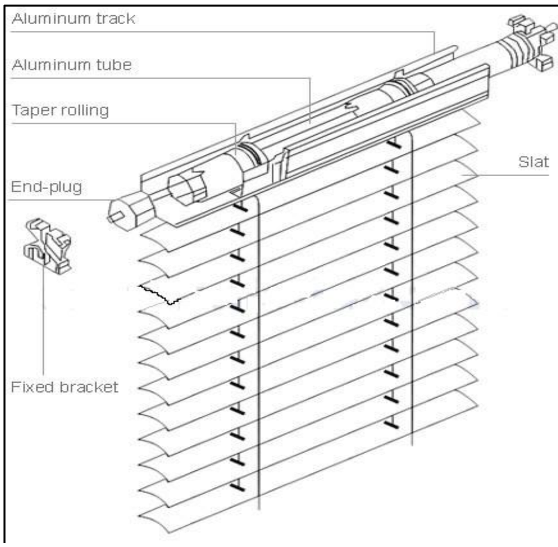


Figure 2.3: Drawing of motorized Venetian Blinds (Left) and remote controlled Louvre Windows with Curtains or Blinds(Right)

Various photometric and control studies has been done on this system.As it is a common but optically-complex fenestration system, the light distribution in the interior can not be predicted reliablly.This issue causes barrier for integrated lighting control strategies to function[3].Also, the issues of over-heating,pollutant dispersion and ventilation are generated by complex pattern of wind flow through this system.In 2019 ,this architectural perspective also is being studied and adressed [4].

C. Skylights:

Skylight can hugely improve energy efficiency, illuminate low-light areas, and enhances overall visual comfort &satisfaction. When used in combination with vertical windows, the performance of combined system is more energy efficient. It can admit more than three times as much light as a vertical window of the same size and distributes the same uniformly. All types of skylight fall into two main categories – fixed and vented. Fixed skylights are non-controllable and only provide extra light. The vented skylight can be controlled, either manually or via remote, depending on the type of skylight unit. Different shapes and sizes of skylights are now commercially available [5], such as, Pyramid, Dome-shaped, Barrel Vault, Curb-mounted, and Ridge type, with varying control options. Laser-cut light-deflecting panels and single/multi-layered glazing are now used with skylights. It controls important design variables such as Visual light Transmittance (VLT), Solar Heat Gain Coefficient (SHGC), and UV components.

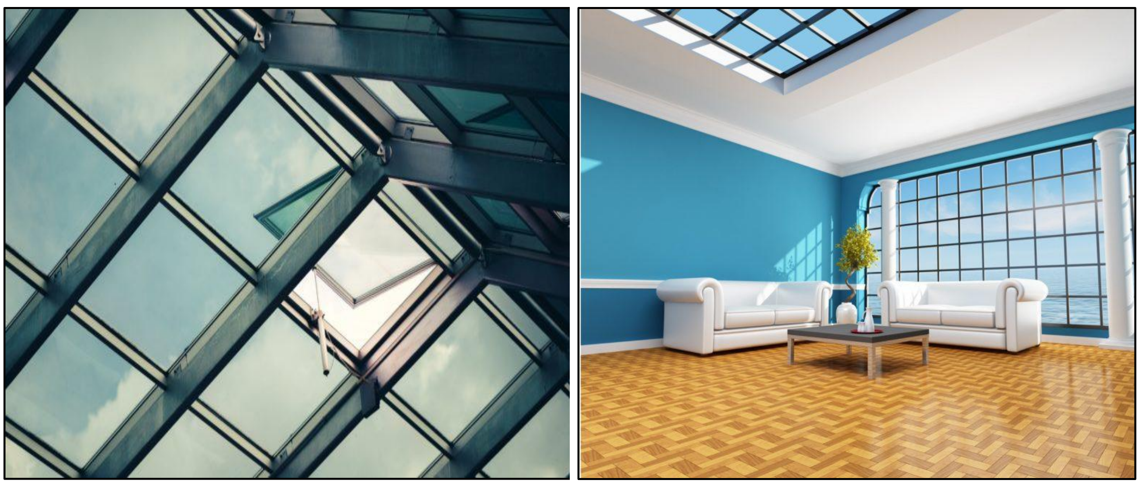


Figure 2.4: Ridge-Shaped Skylight (Left) and use of skylight with window system (Right)

Different studies have been done to effectively design control of skylight integration in modern buildings. Some of them are targeted to find the exact shape and size of skylight in a particular location for lighting/architectural design purpose [6].Recent sustainability and energy efficiency studies reveal that roof skylight systems should be designed both to limit light during periods of maximum daylight to avoid such problems as glare, flare, and so on; and to direct light indoors as fully as possible during periods of limited daylight [7].Also the thermal performance studies can show on the convective heat transfer within cavities of multi-glazed domes[8].All these studies are focused to largely improve performances and usability of skylight systems.

One particular type of skylight is the 'Tubular Light Guides' or 'Daylight Pipes' ,which is the main focus of our study and will be discussed in details in subsequent sections.

D. Anidolic Daylighting Systems:

Anidolic ceiling systems use the optical properties of compound parabolic concentrators to collect diffuse daylight from the sky; the concentrator is coupled to a specular light duct above the ceiling plane, which transports the light to the back of a room. The primary objective is to provide adequate daylight to rooms under predominantly overcast sky conditions. The system is designed for side lighting of non-residential buildings.

Non-imaging optics principles are used to build the solar concentrators of anidolic lighting systems. It is an efficient system for collection and redistribution of the diffuse component of daylight. Because the external anidolic device collects diffuse light rays with high optical efficiency, the anidolic ceiling is most suitable for lighting rooms with diffuse daylight during overcast conditions [9]. Although, if proper solar blinds are installed to protect against glare and overheating from direct sunlight, it can be used in any latitude and any sky conditions.

Basically the system has three basic parts:- external collector- to collect and concentrate the diffused light, light duct- to carry large amount of light flux , and parabolic reflector-to distribute the flux into the room and reduce glare. All these systems are shown below.

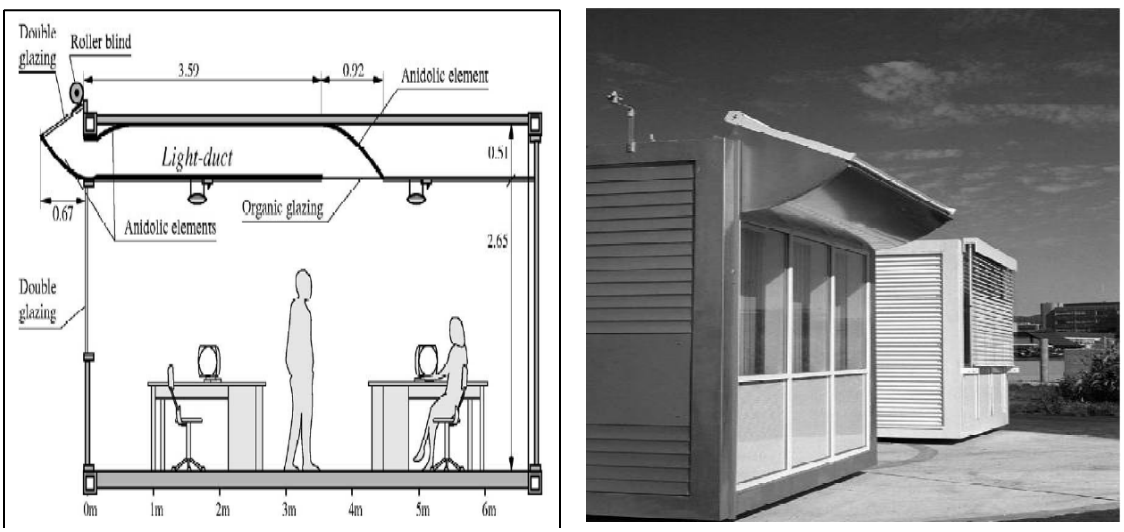


Figure 2.5: Anidolic ceiling installed in a 6*6*3.5 meters room (Left), Front view of the test module[10] equipped with the anidolic ceiling (foreground) and the reference module (back-ground)(Right)

Recent studies have confirmed that the ADS application could be a promising solution for daylighting problems in tropical regions. Both east and west facing collector may be used to improve performance in both half of the day [11].

2.2 Daylight Pipes (DLP)

The Tubular Daylight Guidance System (TDGS) technology redirects daylight into core areas of buildings that cannot be lit using conventional glazing. It is also known as ‘daylight tubes’, ‘sunpipes’, ‘tubular skylights’, ‘tubular roof lights’ or ‘sun tunnels’. They comprise a device for capturing light, a transport section lined with a highly efficient optical material and a means of distributing the light within the interior.

It is the **most commercially successful method** of daylight guidance [12].Modern TDGS were introduced some 30 years ago. They are now manufactured in large numbers worldwide and installed in a wide range of building types.

The largest market sector for TDGS is user-owned domestic deep-plan buildings, although are now installed in many working environments such as offices, light industry and health care buildings.

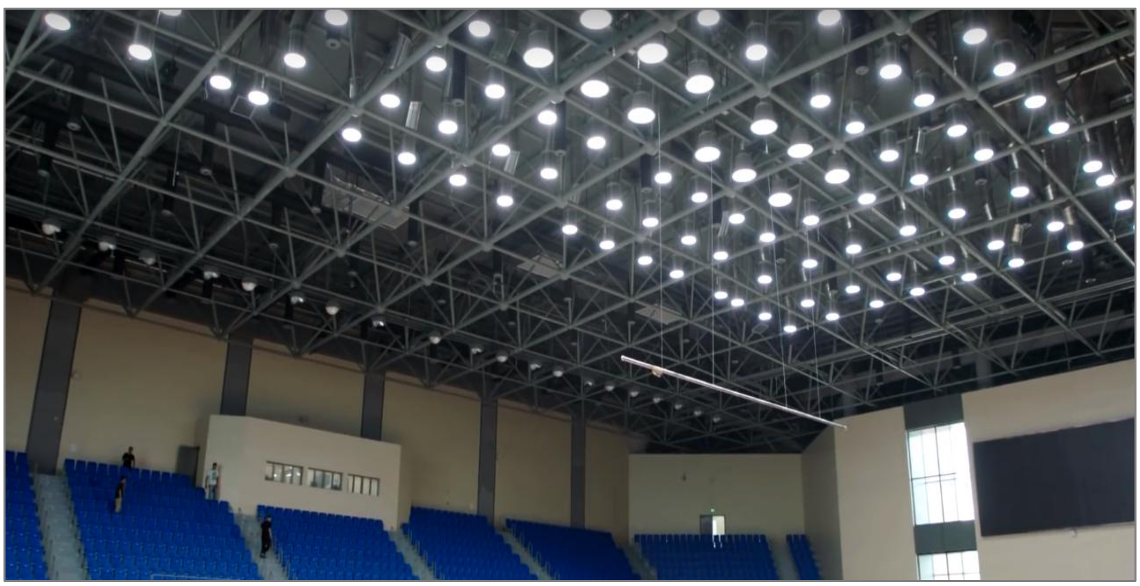


Figure 2.6: Image of Solatube Daylight Pipe installed in an indoor stadium, Beijing

Components of basic daylight pipes:

A) <u>Collection devices</u> :

The collectors consist of a clear polycarbonate dome at roof level which captures both the sunlight and skylight, i.e., global illuminance. They are suitable to use in all altitude. The amount of collected light depends on the 'cone of acceptance' of the collector, which in turns, depends on the shape, size, geometry and mounting style of the collector. Studies have shown the relationship between the cones of acceptance with light collection.

- Acceptance is over the full hemisphere, all light is intercepted.
- Acceptance is within a 120° cone facing the Zenith; some82% of light from a CIE overcast sky is collected.
- If the surface is tilted 30° from the vertical on an azimuth exposed to direct sun, this value reduces to 73%. [13].

Recent modifications of collector:

For locations where sunny condition predominates above 35° latitude, collectors can be enhanced by the addition of devices which intercept low elevation direct Sun.

a) Use of Laser-Cut-Panel (LCP): LCP is made by cutting an acrylic panel so as to produce an array of transparent rectangular elements (Figure 2.7).It uses refraction and total internal reflection, to deflect incident light into the interior of collector dome.
LCP increases the amount of light collected at low solar elevations (up to 50% during winter months) but reductions of the order of 10% at high solar elevations. Thus, LCP levels out the amount of light collected throughout the day. This is more effective in sunny conditions but in the overcast sky, it slightly reduces the amount of light collection.

Figure 2.7: Modification of basic collector: Laser Cut Panels (Left) and Light Scoops (Right), product of Solatube International, Inc.

b) **Light Scoops:** It is placed inside the collector dome, intercept direct sunlight and deflect it into the transport guide. It is most useful in the sunny conditions of higher latitude (greater than 35 °), at lower sun elevations (winter season).

B) <u>Light Transport/Light Guides:</u>

The function of light guides is to carry light from collector to output device with minimum loss, using specular reflection.

The main design considerations in this case are aspect ratio (Length/Diameter of the pipe) and specular reflectance. Clearly if the distance of targeted room and the roof is higher, aspect ratio is higher, and loss increases largely. So the importance is given to the use of materials with higher specular reflectivity. Commercially available guides now generally use reflecting materials like polymeric multi-layer optical stacks with reflectance of 99.6%. As per the **CIE technical report 173:2006,** relation between reflectance and light loss has been shown on below table-

Aspect Ratio(L/D)	350 mm diameter		530 mm diameter	
	RF=95%	RF=99.6%	RF=95%	RF=99.6%
1	93%	99.5%	93%	100%
5	77%	98%	80%	98%
10	62%	96%	65%	96%
20	40%	92%	44%	92%

Bend Angle	350 mm diameter		530mm diameter	
	RF=95%	RF=99.6%	RF=95%	RF=99.6%
30	35%	2%	10%	2%
60	50%	7%	13%	2%
90	58%	8%	22%	3%

Table 2.1: Overall light transmittance of straight circular cross section guides for different aspect ratios and specular reflectance [14] (Top)
Table 2.2: Losses for a single bend of various angles for guides and specular reflectance [14] (Bottom)

Use of prismatic materials in guide-walls: Instead of using mirrored surfaces, precision optical materials made from acrylic or polycarbonate can also be used to enhance the light carrying capacity. They consist of a tubular structure in which light is totally internally reflected from a prismatic dielectric surface which traps the light and redirects it down the length of the guide.

C) <u>Output Devices:</u>

Main function of output device is to uniformly distribute the light received from light transport system. It also serves the purpose of heat blocking and shutter options.

The most common type of commercially available output device is a polycarbonate circular flush or domed diffuser made of opal or prismatic material of diameter almost equal of the light guide.

Devices using Fresnel lenses are also available. Some output devices include a clear 'double glazing' sheet to decrease heat transmission. Shutter systems are also used, either within the guide or in the output device, to block unwanted light.

<u>Daylight Pipes and Buildings:</u>

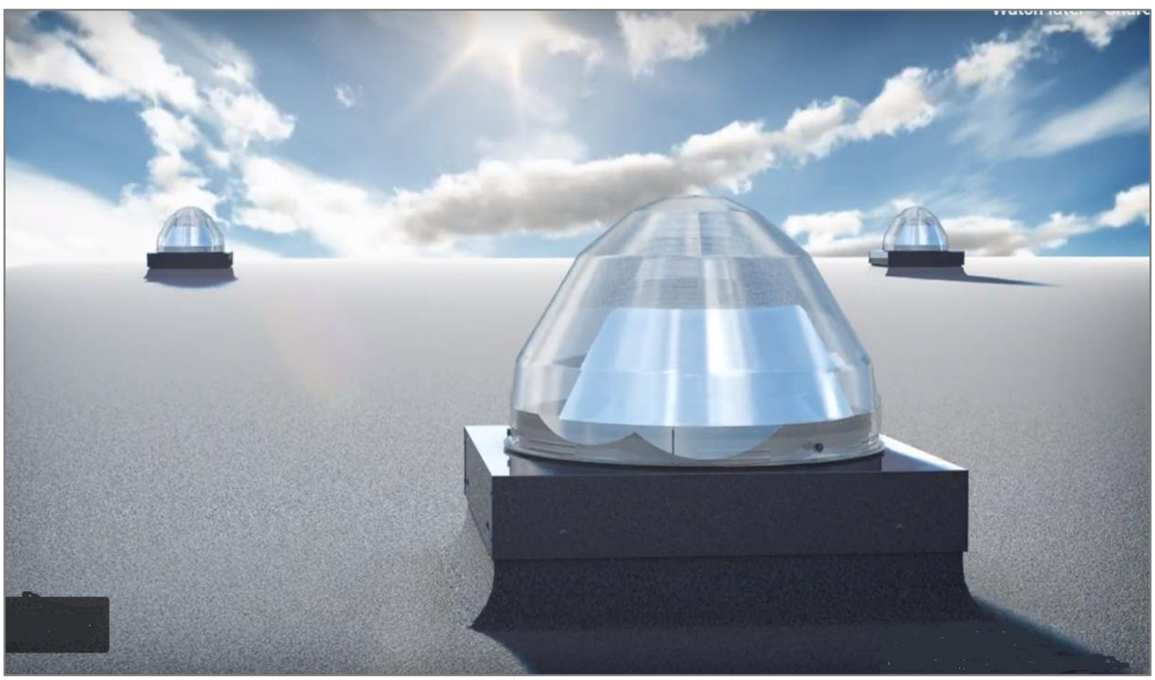


Figure 2.8: Representative image of daylight collectors installed on roof

- **Usage and costing:** Daylight pipes are a more expensive method of delivering daylight to building interiors than windows and conventional roof-lights but have the capacity to deliver daylight into areas of deep-plan buildings which the latter cannot. TDGS are of the order of 50% more expensive than electric systems while delivering similar levels of illuminance. The largest market sector is the user-owned domestic buildings, and produces high user satisfaction in this sector. It is also used extensively in working environments also.

The use of small conventional vertical windows to supplement TDGS produced high levels of user satisfaction with high reduction in lifetime cost.

- **Thermal Performances:** Generally, thermal performance of a building equipped with daylight pipes is comparable with that of a similar building with conventional windows or roof-lights. This is because they have much smaller external surface areas compared with other daylight devices, but their thermal performance is broadly similar.

- **Fire Protection:** As all building components must comply to the fire protection guidelines, a number of design techniques and devices, such as fire stopping and fireproof ducts, may be used to prevent the spread of fire between building compartments via pipes. But daylight pipes present no greater risk of propagation of fire between buildings than other conventional lighting systems.
- **Other Considerations:** Light collection devices must take necessary precaution to prevent water ingress but present few structural problems due to their negligible weight. Guides paths must not lie in the path of structural elements such as beams. The layout of output devices must be coordinated with that of the electric luminaries.

2.3 Daylight Integration with Artificial Indoor Lighting:

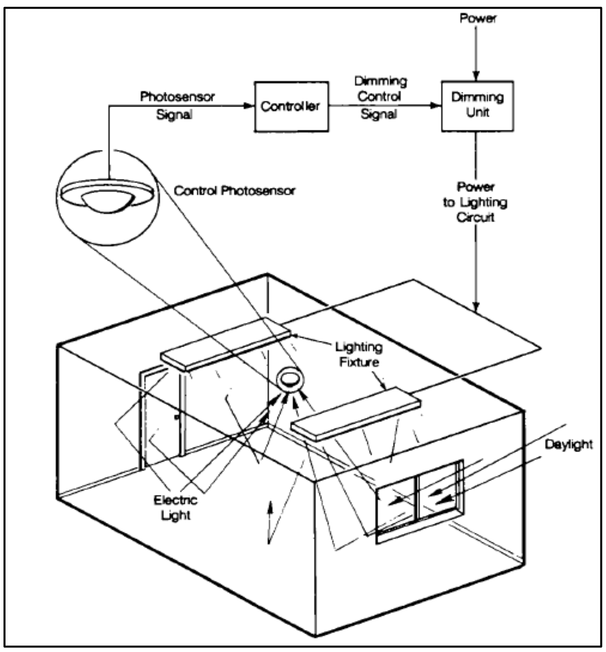
The main purpose of daylight responsive dimming systems also known as daylight-linked automatic lighting control systems are to maintain target illuminance levels at the work-plane regardless of the amount of available daylight in the interior space. To do this, the electric light output is continuously adjusted based on the changes in available daylight measured by photosensors. This system is being used to improve both the quantity and quality of the visual environment, and can significantly reduce the electric lighting requirement.

The focus of initial studies for successful daylight integration was to study, develop, and measure the performances of open-loop, closed-loop and integral-reset control strategies for different daylighting systems. These studies consider only the light level as predominant factor for visual performance. As the concepts of biological effects of lighting and human centric lighting were developed, the visual performance and user satisfaction parameters of lighting became important. Since mid-2000's, efforts has been made to address these parameters, including the light level. Development direct digital control (DDC), computer interfaces, and easily controllable (light output, CCT, CRI) LED's, has helped to shift the focus of lighting control to be more human centric.

The Basics of initial control strategies:

Rubinstein and others (1989) [15], Choi and others (2005) [16] developed and studied some of the first conventional and modified control algorithms. The conventional system had essentially below components-

1. A photo-sensor for measuring the light level within or entering the controlled building space. The sensor signal was sent to controller.
2. A controller that incorporates an algorithm to process the signal from the photo-sensor and convert it to a control signal to the dimming unit.
3. A dimming unit that smoothly varies the light output of the electric lights by altering the amount of power flowing to the lamps.



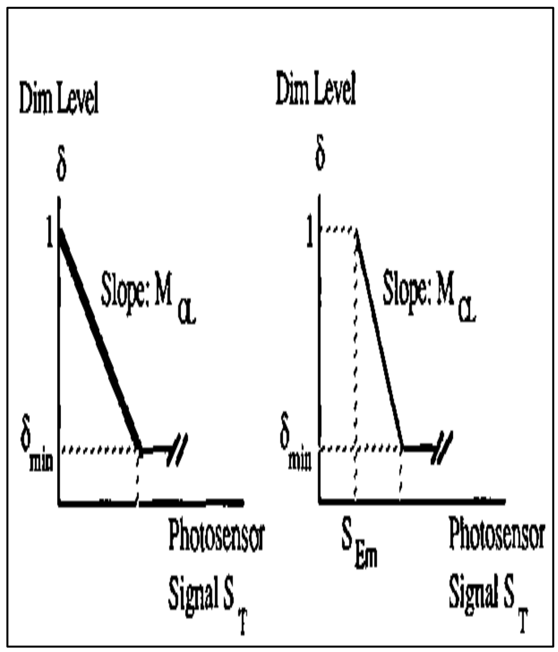


Figure 2.9: Photoelectric dimming system components in typical daylighting application (Left). And relationship/transfer function between total photosensor signal, ST, and fractional dimming level, δ, for open-loop proportional (Right-Center), closed-loop proportional control (Extreme Right) algorithms. The fractional dimming level can vary between δmin and 1 (full light output) [15]

In the case of **open loop strategy**, the sensor only detects the daylight level. This was done by a ceiling mounted photosensor, directed to the center of the window, thus measuring the external horizontal illuminance.

The open-loop proportional control algorithm simply establishes a linear relationship between the detected photosensor signal and the dimming level. As the daylight stimulus exceeds zero, the electric lights dim along a line of slope M as shown in Figure 2.9. As the system sensitivity and reliability depends on slope M, daytime calibration of M must be done.

In the case of **close loop strategy**, the photosensor detects the total light (controlled electric light as well as daylight) available in the room at any time. The controller adjusts the electric light output so that the dimming level, δ, is a linear function of the difference between the photo-sensor signal and the night-time reference level. As with open-loop proportional control, a daytime calibration must be performed to adjust the system sensitivity so that the slope of the response (M in Figure 2.9) is appropriate to the specific room and daylight conditions.

The ratio of photosensor signal to daylight workplane illuminance (the slope M) varies with sun and sky conditions. This variation leads to poor performance (under-lit and over-lit spaces).To address this issue, some attempts were made to improve the system by developing a relation between slope M and sun and sky conditions. An improved closed loop system was developed by Choi and others, 2013 [17], and reported 9.46 lx and 16.43 lx difference between predicted and measured illuminance value.

Most of the recent studies on daylight control strategies, targets to provide user satisfaction and comfort, along with the targeted illuminance levels. Instead of standalone system, use of central controller has improved the overall design in respect to Building Management Systems (BMS) integration. In this approach, the interior space is divided into multiple control zones, and for each zone, real-time illuminance level is measured by dedicated sensors [18]. These data is fed into central controller, from where the dimming level for each luminiare inside the room is decided. Clearly, the daylight contribution data for each zone not needed here.

The user satisfaction varies largely on age, mood, and task performed by a user. Machine learning systems, fuzzy logics and neural networks technique can be used to find a particular user's experience upon varying lighting control. X WANG and J-PMG LINNARTZ (2016) developed an intelligent lighting control system [19], where they **mathematically modeled the user satisfaction** index by using some satisfiers. These user satisfaction models can be incorporated in the controller algorithm, to find a user specific lighting control system.

2.4 Different Approaches to Study the Light Transfer Characteristics of Daylight Pipes

The photometric properties and light transfer characteristics of daylight pipes are two major aspects for an illumination designer perspective. To study these important design parameters, different approaches has been studied and established since the innovation of tubular light guide system, long back since 1985.All the studies can be categorized into three basic types for the sake of literature. Some of them concentrate to develop an analytical and mathematical model of light transfer through ray-tracing methods, with the idea to develop computer simulation tools. Some others studies focus to develop a generalized model, by combining measurement results of both laboratory simulation and real-life installations of daylight pipes. Recent studies try to combine the real life installation measurements and software generated results for enhancement of overall technology. Though all the approaches are covered here, our main focus will be to find a method to analyze daylight pipe characteristics in most simplified way and with minimum logistical issues. That method we must use for our laboratory experiment purpose. Three approaches are described in details, through examples, below-

1. **D J Carter** , in his paper published in **2002**, presented a detailed structure of photometric **performance analysis and prediction methods**[20] for solar light pipe systems .In this work, the total luminous flux output ,luminous intensity ,and planar luminous distribution was investigated by using a combination of laboratory experiment results and field measurements.

Experimental set-up:

Two light pipes of 330mm diameter (D) and length (L) of 610 mm & 1220 mm, with opal diffuser output, were installed in a roof space of Mulberry building, university of Liverpool. An apparatus was designed, based on an optical length of 1 meter, and installed beneath the pipe, so it can measures the luminous intensity at gamma(0°-90°) and for to C planes (0° and 30°). Light was measured using calibrated photo-cells; connect to data-logger, which also measures the external illuminance simultaneously.

A 0.8*0.8*0.8 m cubic box with a centrally mounted photocell was used to measure the luminous flux output, thus approximating a photometric integrator.

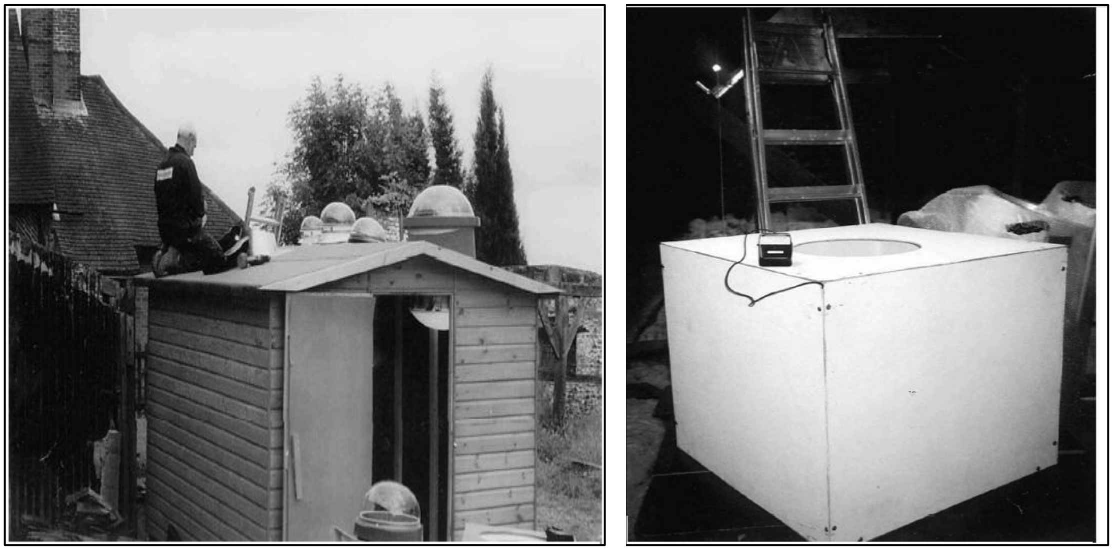
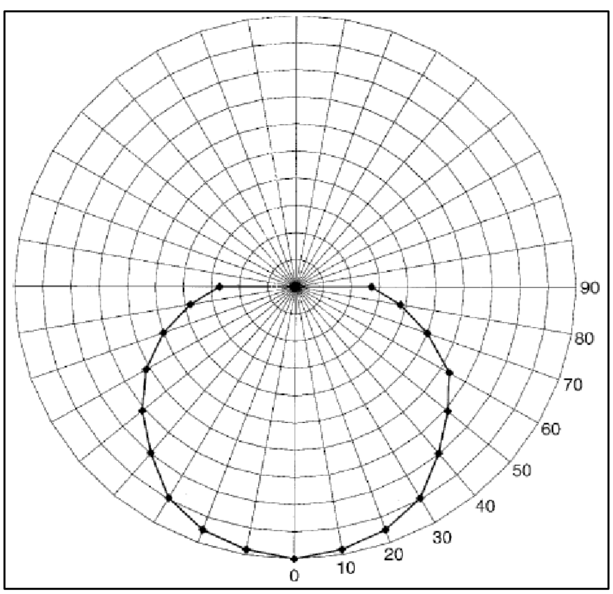


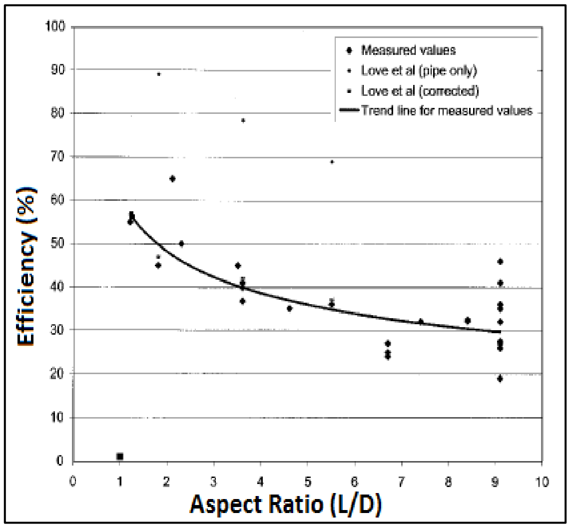
Figure 2.10: Test setup (Left), and Photometric integrator for luminous flux measurement (Right)

Results: In predominantly overcast/cloudy sky conditions, the readings were taken, and the gamma plane values were averaged and plotted to generate intensity distribution polar curve. Using nadir illuminance values of the integrator set-up, total luminous flux output was calculated by the **Zone Factor method**, described in CIBSE TM 5.Both results are shown in figure 2.11.



Installation Name	Measured Luminous Flux(lx)	Predicted Luminous Flux(lx)
Mulberry Building 1	585	578
Mulberry Building 2	371	414
Pleasant Street School 1	569	523
Pleasant Street School 2	540	500

Figure 2.11: Polar curve of average luminous intensity distribution for overcast sky (Nadir intensity =295 cd/10001m) (Left) and, the measured and calculated luminous flux output (Right)



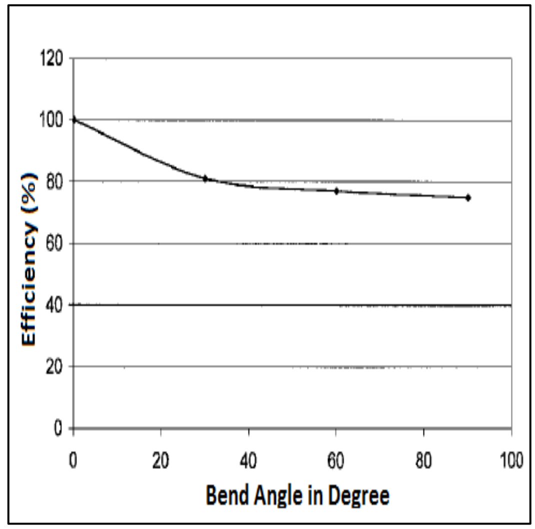


Figure 2.12: Graph of pipe efficiency against aspect ratio(Left) and, Graph of efficiency against bend angle for bend length equal to pipe diameter(Right)

Using these experimental data, 4 other field measurement data, and some of previous study result[21], the relationship between pipe efficacy and aspect ratio(L/D) was drawn (figure 12).the plot of pipe efficacy and bend angle was plotted using same study[[21] .

Proposed Prediction Model:

a) Total luminous flux exiting the diffuser is product of external illuminance, pipe-cross-sectional-area, and system efficiency. As figure relates pipe efficiency with aspect ratio, and also pipe efficiency with bend angle, the total efficiency is multiplication of these two data. In this way, the total luminous flux can be found for different size and shape of daylight pipes.

b) Illuminance distribution can be found using the cosine law of illuminance. Calculations were made using known luminous flux and intensity distribution same as table 2. Table shows the measured and calculated value of light level on floor plane.

Location	Measured (lx)	Predicted (lx)	% error
Nadir	22.5	21.7	4.4
1 m from nadir	17.3	17.3	0.0
2 m from nadir	7.5	7.3	2.6
3 m from nadir	5.0	4.3	14.0
4 m from nadir	4.0	3.4	15.0

Table 2.3: Measured, and calculated planar illuminance, where, external illuminance = 9700 lx, average luminous flux output from pipes = 371 lumens.

The computer simulation concepts made by Carter are not detailed here. Simulation methods will be discussed later.

2. A rather simplistic way to study and analysis of light distribution of light pipes was presented by **Calin Ciugudeanu and Dorin Beu,** in their paper [22], published in **2016**.It is basically a case study for passive TDGS, installed in a residential building, in Cluj-Napoca, Romania. Field measurements and software simulation results are described below.

Experimental set-up:

A light pipe produced by company VELUX (Model – Solar Tunneler TWR 14) of length 2.5m and diameter 350mm was installed in 4m by 4m room. The pipe consisted of an acrylic collector, light guide path with interior surface reflectivity 95%, and white diffuser as an output device.

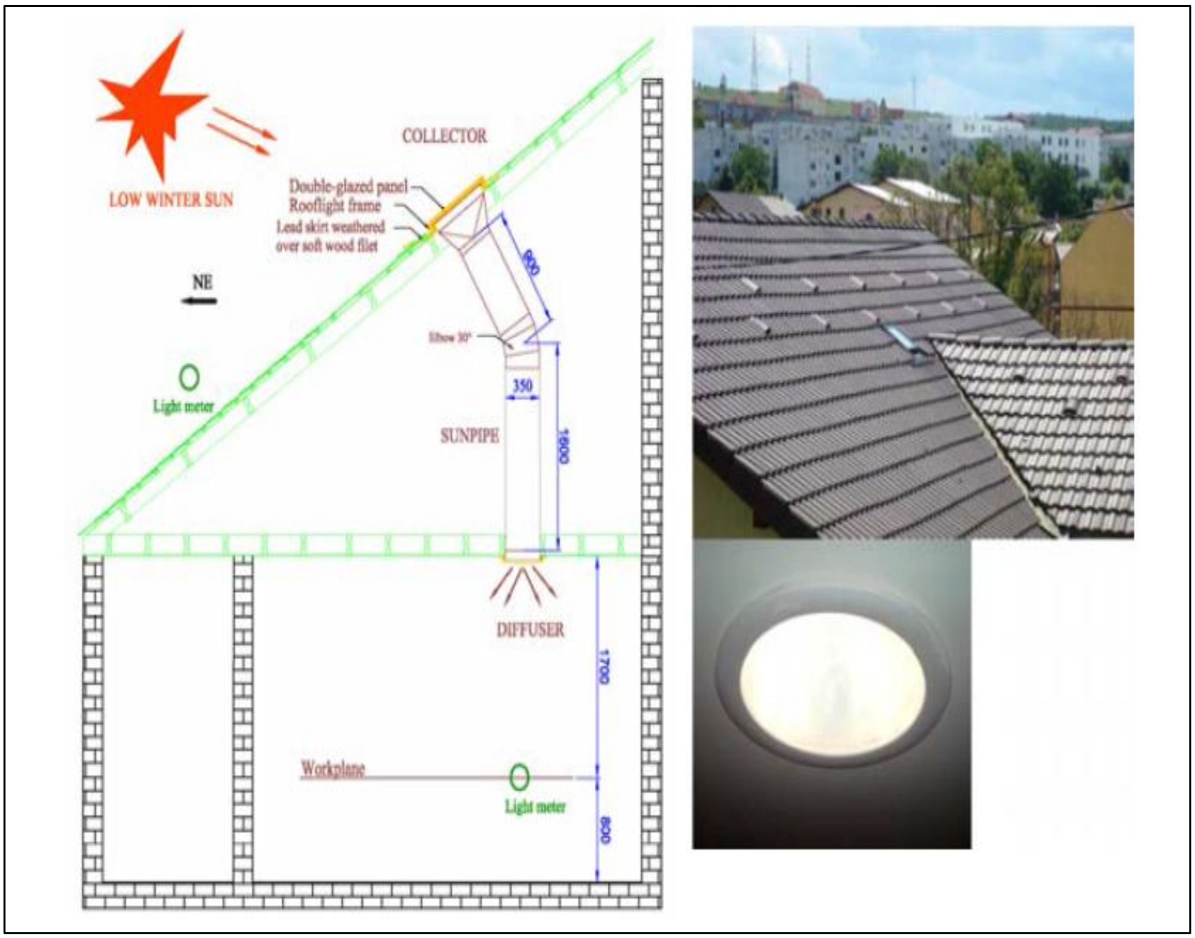


Figure 2.13: The experimental set-up – VELUX TWR14 system installed in Cluj-Napoca, Romania

Results: A standard light meter was placed under the diffuser, at a height 0.8m above from the floor. The minimum, maximum and average value of indoor and outdoor illuminance was calculated for 30 different low-suns, winter days.

Value	Workplane Illuminance(lx)	External Illuminance(lx)	Internal/External Illuminance	Average internal Illuminance per day(lx)
Maximum	238	88000	1.38	206
Minimum	34	3200	0.19	65
Average	151	41926	0.36	145

Table 2.4: Measured average results of above mentioned study [22]

Software Simulation: Since DIALUX 4.7 had the capability to simulate skylights, it was used for software simulation. A skylight was selected in Dialux, with same geometric and structural features, as in VELUX TWR 14 system. The length of the tube, reflection coefficient, and the optical properties of collector and diffuser system, was same in both simulation and TWR 14 system. Geographic location, Latitude, and date& time were also matched with practical study.
The DIALUX calculation was done only considering the indirect sunlight .Results are described and compared below.

Date	Time	Measured Illuminance(lx)	Simulated Illuminance(lx)	Relative error (%)
04.02.09	13.45	135	149	9
14.04.09	13.30	200	208	4
21.07.09	15.00	168	175	9
31.07.09	13.45	238	211	13
Average Relative error				8.7

Table 2.5: Comparison of results for maximum horizontal illuminance-measured and simulated values [22]

Here, DIALUX 4.7 was used for software simulation. Some other computer programs also can be proposed and used.

3. **Analytical Tools:**

a) HOLIGLIM approach: Based on ray-tracing between diffuser and output device, including the Sun, an analytical method , namely Hollow Light Guide Interior Illuminance Method is proposed in [23].Using this method , computer program **HOLIGLIM 4.2** was developed and discussed in above mentioned study.

b) Computer Desktop program **RADIANCE 2.0** can also be used [24]

4. **Product Example**:

There is very limited amount of published work on illuminance distribution of commercially available daylight pipes. Figure shows luminous intensity distribution of 600 mm square output device from Solatube International Ltd.

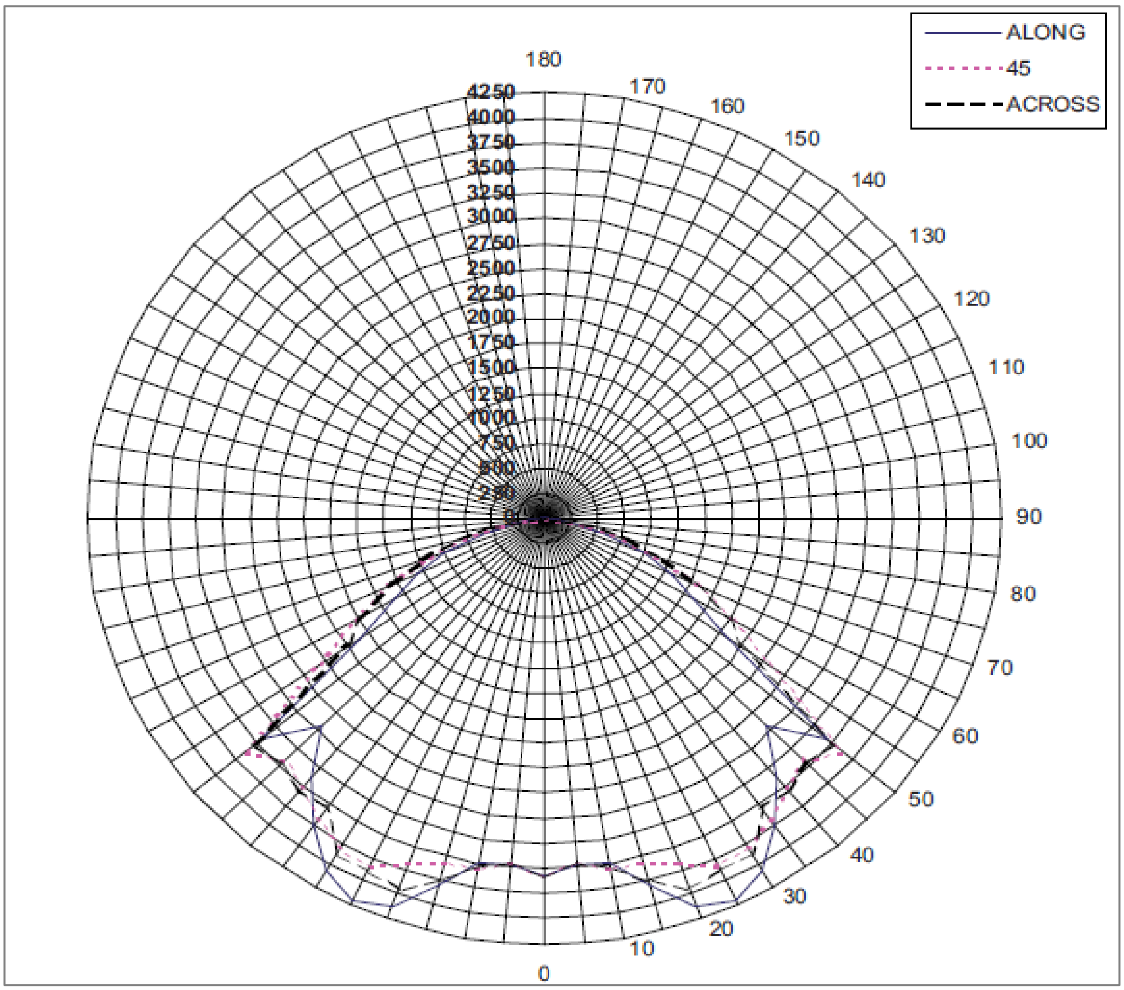


Figure 2.14: Luminous intensity distribution from a 600-mm square output device (Solatube International, Inc.)

3. SYSTEM DEVELOPMENT AND FABRICATION

3.1 Design of the Controller

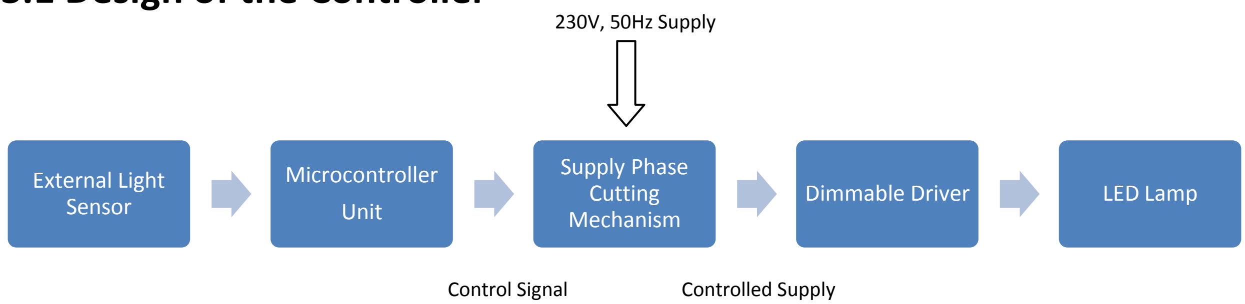


Figure 3.1: Block Diagram of real time dimming controller for LED

In this section, the development of Arduino based LED controller has been described in details. The objective is to develop a real time controller, which controls the light output of LED luminiare with dimmable driver, depending upon real time external daylight availability data. The scheme has been shown in block diagram above. It is basically an open loop control system, that keeps into account that how much daylight is actually entering the room through daylight pipe and available in the task area of the room. According to that, the artificial light level is adjusted to get the targeted average illuminance value on that task area.

All the components shown in the above block diagram are described with functionality, working principle and technical specification in next section.

3.1.1 External Light Sensor

For daylight integration and lighting control purposes, many single-chip Lux meter have been developed and evolved in recent years. Along with high precision Lux measurement, these cheaper semiconductor devices also offers multiple level of connectivity, and thus can be easily used for modern day's integrated control systems. Two main series of these recent products are: -

1. **OPT-300X:** Developed by Texas Instruments, all products within these series can be categorized as light-to-digital ambient light sensor (ALS) with high precision human eye response. Generally these products have a range 0.1 to 83K Lux, which is appropriate for

daylighting operation. They offer both analog and digital output, so both analog communication and communication using I2C protocol can be implemented.

2. **AS- 72XX:** Developed by AMS (Austria Mikro Systeme), all products within these series can be categorized as complete system-on-chip (SoC) sensor-integrated IoT smart lighting managers/controllers. While working only as a sensor, these products can measure a variety of photometric parameter, such as Lux level, CCT, XYZ, DUV, uv (as defined by CIE 1976).These parameters can be used for color-tunable white lighting applications. They offer I2C communication for sending and receiving measured data. Though these products are very useful and upgraded, cost issues and lack of availability limit their usage in current scenario.

In our case we have used TSL 2561, a product of Texas Advanced opto-electronic Solutions, which is a light-to-digital converter, used for general purpose ambient light sensing.

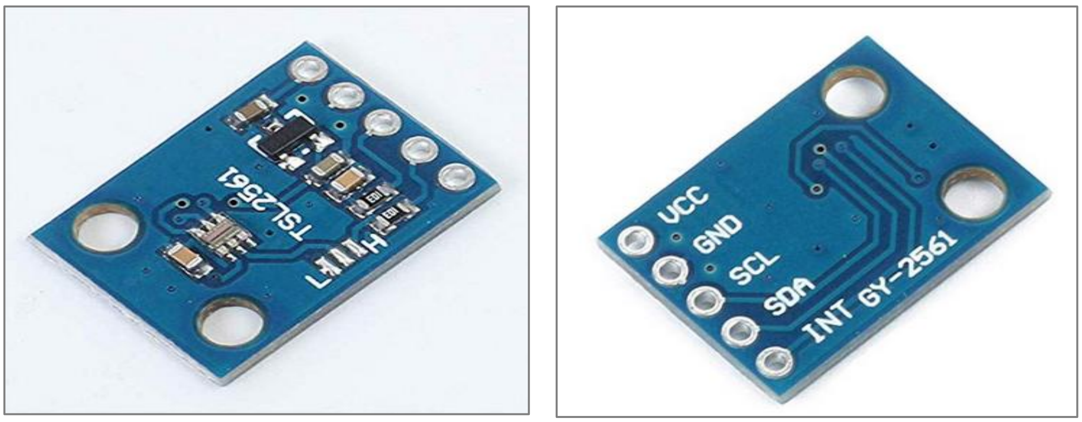


Figure 3.2: Front-side (Left) and Back-side (Right) of TSL-2561 external light sensor

The pins are as follows:

1. V_{cc}: power supply(2.7V to 3.6V) to this chip
2. GND : ground connection for supply
3. SCL: I2C SCL clock pin.
4. SDA:I2C SDA data pin
5. INT: data output pin when operated in interrupt mode.

The prominent specifications of this product are –

1. Approximates Human Eye Response
2. Dynamic range is 0.1 to 60,000 Lux
3. Temperature range is -30 to 80 ° C
4. Programmable Interrupt Function with User-Defined Upper and Lower Threshold Settings
5. 16-Bit Digital Output with I2C Fast-Mode at400 kHz
6. Programmable Analog Gain and Integration Time

7. Rejects 50/60-Hz Lighting Ripple
8. Low Active Power (0.75 mW Typical) consumption
9. RoHS Compliant

3.1.2 Phase Controlling Mechanism

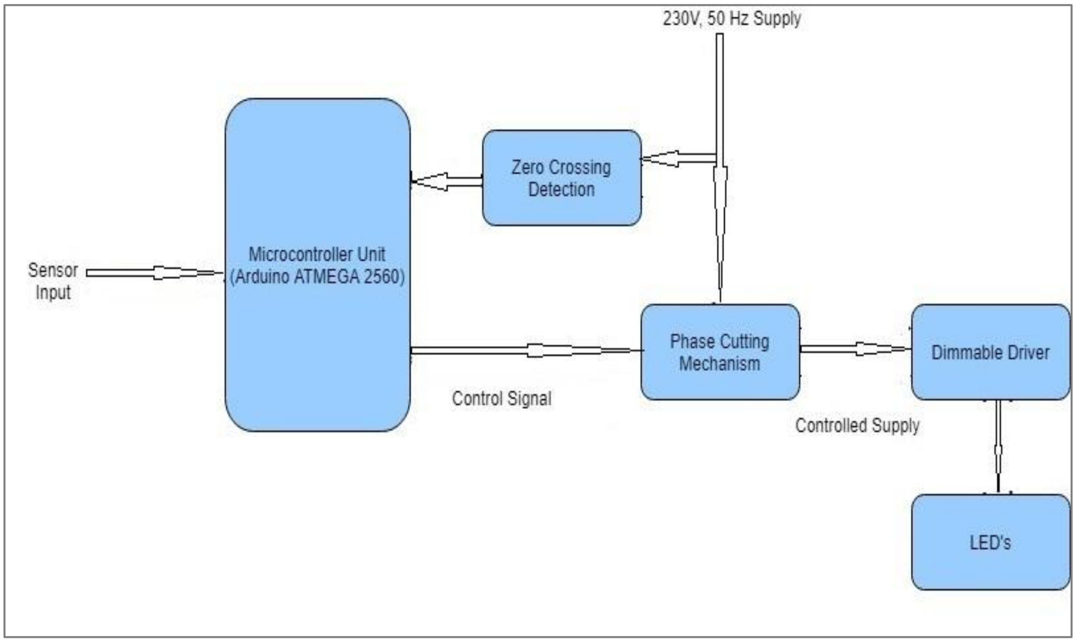


Figure 3.3: Block Diagram of Phase Controlling Mechanism

Here we analyze the steps of controlling AC power supply by phase cutting mechanism.

Phase angle controllers are used to vary the RMS value of AC voltage by introducing Thyristor/Triacs between the load and the supply. It is done by changing Thyristor's firing angle/triggering angle to get the desired RMS output.

In our case, we have used Triac instead of Thyristor and applied triggering in both +ve and -ve half of AC cycle as shown in figure 3.4.

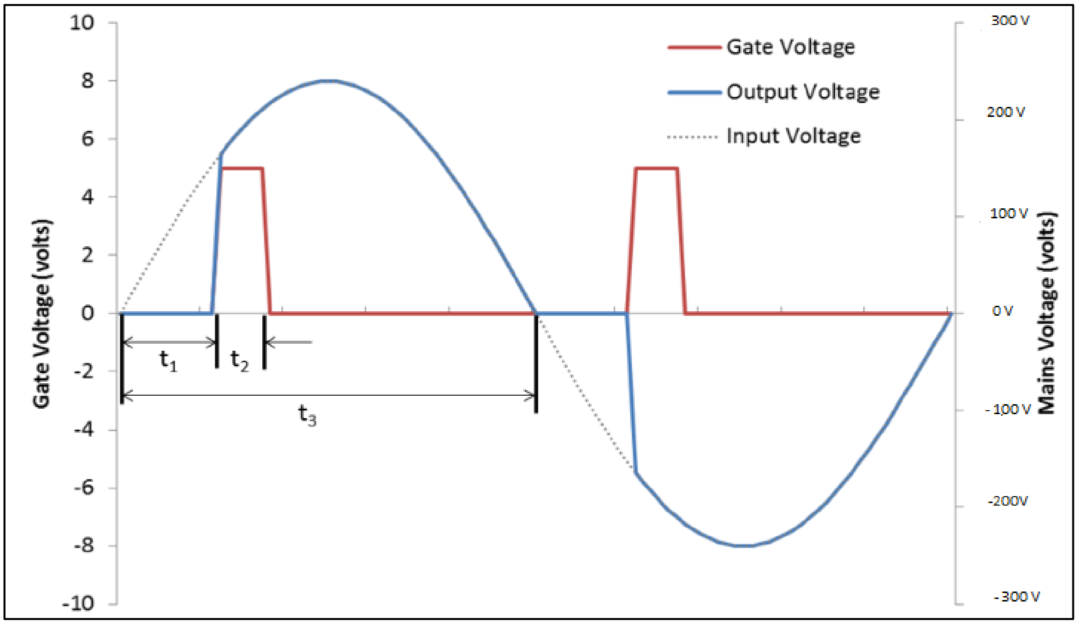


Figure 3.4: +ve and –ve half cycle triggering of Triac

For an AC supply voltage, $v = V_m * \sin \theta$; If a firing angle α is used in both +ve and –ve half cycle then, Output RMS voltage is equal to

$$V_{rms} = V_m \left(1 - (\alpha / \pi) + (\sin 2\alpha / 2\pi)\right)^{0.5}$$

So, by adjusting triggering angle α, RMS voltage output can be adjusted.

- Firstly the zero crossing of supply sinusoid is detected, to time the trigger.
- From the daylight availability data, voltage needed for the LED is calculated in real time. As per the voltage required, the wait time (firing angle) is calculated. The Triac should wait for the specific time, at OFF mode after zero crossing. After this time, the pulse for Triac gate drive is generated and Triac is switched on.
- The Triac must supply the required current for the LED load. If multiple LED's are connected, or current required is higher, the Triac should be chosen accordingly.

The overall circuit representation of the above block diagram is shown in below figure:

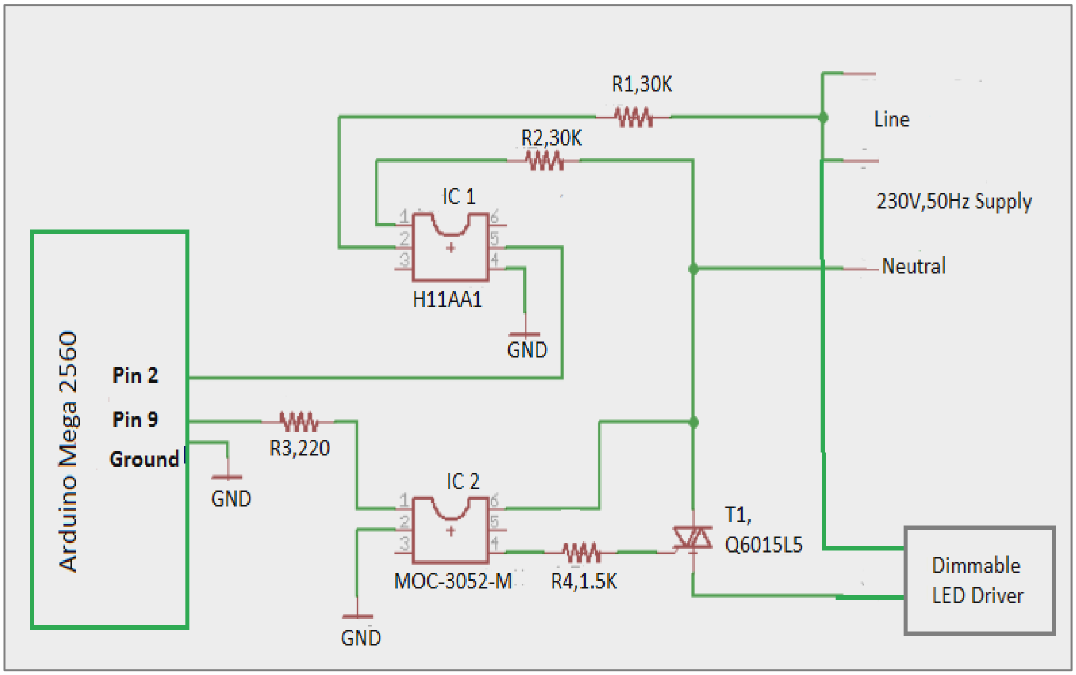


Figure 3.5: Circuit components of Controller and LED Driver

3.1.2.1 Sensor Input

AS discussed earlier, we are using TSL-2561 sensor for external daylight availability measurement. The internal working of TSL-2561 has been shown in below figure:

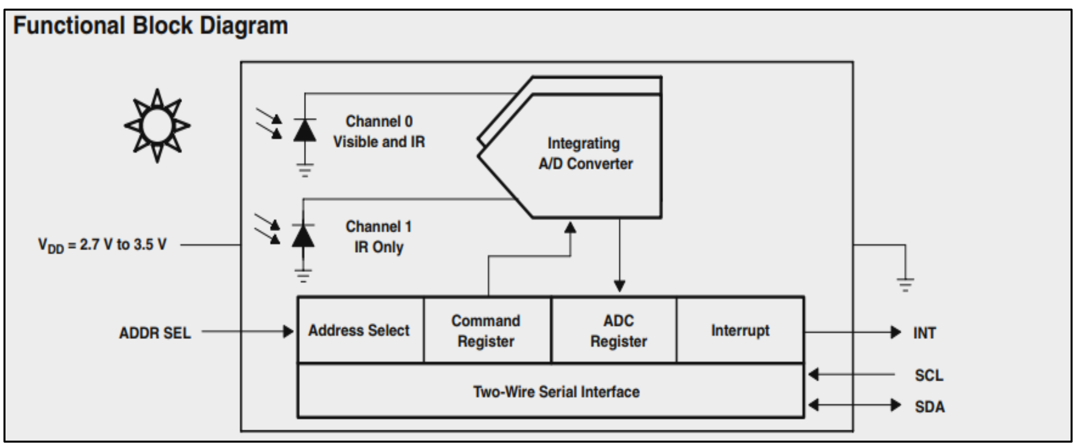


Figure 3.6: light-to-digital-converter TSL-2561 external light sensor

Now, as per the basics of I2C communication, TSL-2561 can be connected and read by any type of Arduino microcontroller. Next figure shows the basic connections of I2C communication with Arduino-

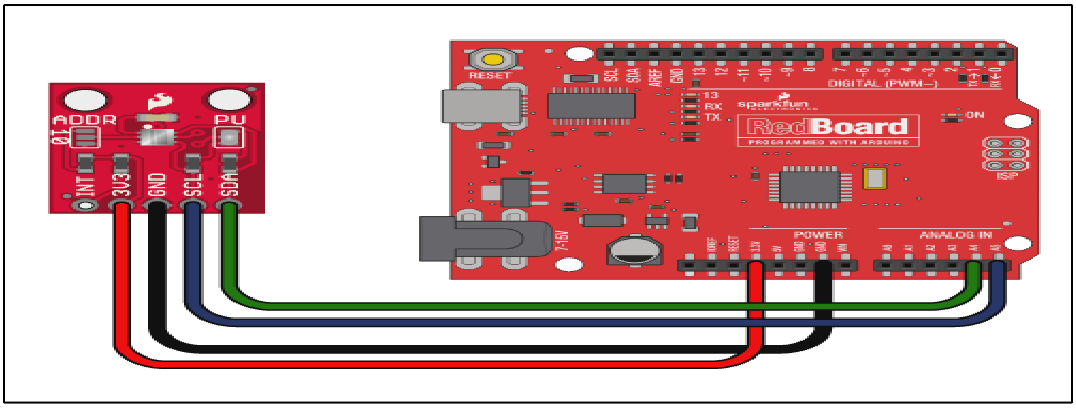


Figure 3.7: Representative figure where TSL-2561 connected with Arduino Red (Same approach to be taken for Arduino Mega 2560 in this work), (Here A4,A5 pins SDA and SCL comm's of Arduino respectively)

So, clearly, TSL-2561 coverts the Lux level into hex data and send it via I2C protocol. It can be easily read by the Arduino microcontroller. Several libraries have been developed to read this digital data and back-convert it to original lx. We have used _Adafruit_Sensor.h_ and _Adafruit_TSL2561_U.h_ libraries, (as hex files), to simply process the sensor digital data.

Also, the sensor output, (Lux level) must be calibrated with the standard Lux-meter. The calibration data are provided in the Annexure section.

3.1.2.2 Supply Zero Crossing Detection

To detect the zero crossing of the supply, we have used H11AA1, which is a 6-pin DIP AC input/transistor output opto-isolator, used specifically for both half zero cross detection.

It consists of two Gallium-Arsenide infrared light emitting diode which are connected in inverse parallel and optically coupled to a monolithic silicon phototransistor detector.

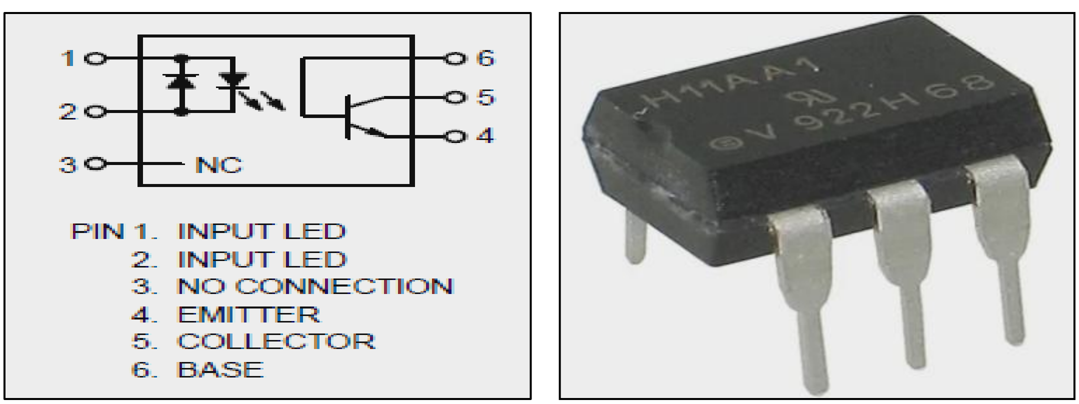


Figure 3.8: H11AA1 pin diagram (Left) and component image (Right)

So, whenever there is any supply voltage (any polarity) between opto-coupler's pin-1 and pin-2, light is emitted. So the transistor keeps conducting the pin-2's +5 Volt to ground.

Only when the supply sin-wave crosses zero, the transistor gets open-circuited, and a narrow peak is obtained in pin-2. That's how Arduino detects the zero crossing.

3.1.2.3 Microcontroller unit (Arduino Mega 2560)

It is microcontroller board based on ATMEGA 2560 .It contains 54 digital input/output pins (including 15 PWM pins), 16 analog input pins, 4 UART ports and 16 MHz in-built crystal oscillator and other hardware and communication ports to support the microcontroller unit.

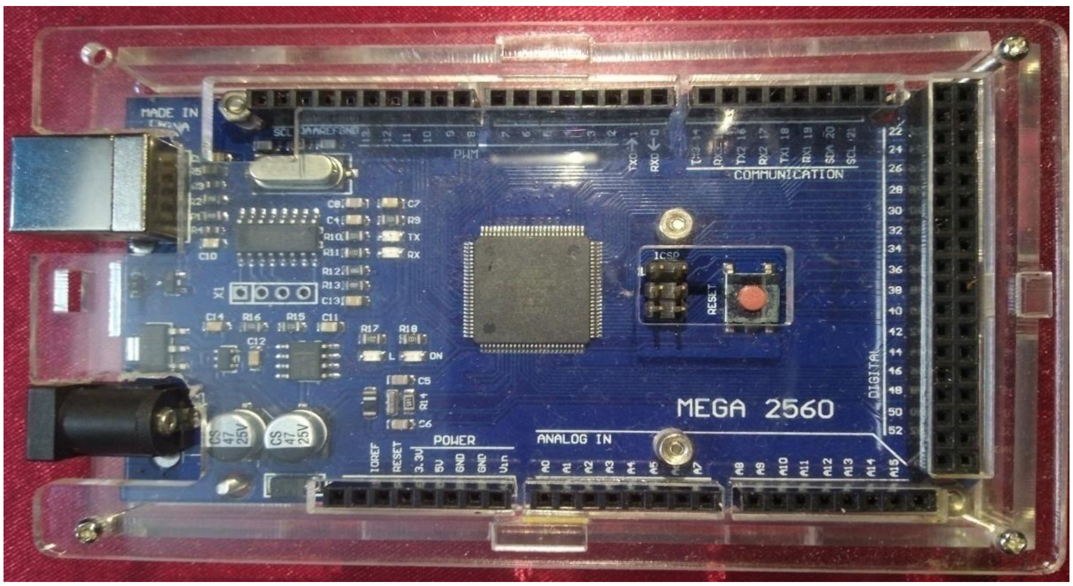


Figure 3.9: Arduino ATMEGA 2560 board

Some technical specifications of the board that we are going to use in our work are given below:

- **Power supply** to the board is given via USB connection. Also non-USB supply from either AC-DC adapter or battery can be given, for that, recommended supply voltage is 7-12 volt.
- There are 54 I/O pins, among them are the **PWM pins** (pin-2 to pin-13 and pin-44 to pin-46), to generate PWM output using *digitalWrite()* function.
- **RX-TX communication** (Pin No-0&1, 18&19, 17&16) functionality, to receive and transmit TTL serial data.
- **I2C communication** (Pin No-20(SDA) and 21(SCL)) to support Inter-Integrated circuit protocol (I2C) to use the device in master-slave mode.

- ***Interrupts:*** The job of the interrupt functionality is to make sure that the processor responds quickly to important event. When a certain signal is detected, an Interrupt halts the processor's current execution of code, and executes some code designed to react to whatever external stimulus is being fed to the Arduino. Once that interrupt routine code is executed up, the processor goes back to its previous execution.

It is the best possible way to monitor real-time external events. It can used to detect a rotary encoder, sudden change of a sensor or monitoring user input like a button press or potentiometer changes. In our case, we use the interrupt for zero cross detection.

Pins available for external interrupt are pin no -2, 3, 18, 19, 20, 21.The syntax for attach an interrupt with a digital pin is *attachInterrupt(digitalPinToInterrupt(pin), ISR, mode).* The "mode" here to define the change of input(like the pin is going LOW to HIGH or HIGH to LOW etc.).

Interrupt Service Routine (ISR) is that piece of predefined code/instruction that the processor must do when an interrupt has occurred. For high speed operation, like detecting zero crossing of AC sin-wave, the ISR must be short and fast. So, it should not include any delay commands. Also the ISR does not take any parameters and returns void. Thus, it only can connect to outside (main) code through volatile global variables.

The main function of the microcontroller board is to collect the external sensor data and generate the Triac gate drive pulse. As discussed before, the Triac gate drive pulse regulates the ON time and the OFF time of the Triac to control the voltage. This precise timing is done by the Arduino interrupt services and timer control registers and counter. A program has been written to generate the PWM pulse for Triac gate drive. Before diving into the Arduino program, we should first look into the OFF time calculation procedure. The timing sequence algorithm and after that the steps of overall program is discussed in details in next segment.

<u>Representation of sine-wave time period in terms of Arduino clock pulses</u>:

For a certain value of required artificial light contribution, a certain RMS voltage is needed. As we can see in the governing equation of Triac output voltage, for required RMS voltage, the firing angle α can be found. For Arduino programming purpose, the value of firing angle must be converted in terms of time.

The Arduino in-built oscillator and timer run at 16 MHz. If a frequency divider of 256 is used (Via timer control registers), reduced frequency = $(16\ \mathrm{MHz}/256)$

Thus time taken for one clock period = $256/16$ micro-seconds.

Again, for a 50 Hz supply, time taken per period = 0.02 second.

So one cycle of 50 Hz supply means, $(0.02*16*10^{\wedge}6/256) = 1250$ clock pulses of Arduino timer (when 256 frequency divider is used).

So a half cycle of 50Hz sine wave can be represented as $(1250/2) = 625$ clock pulses or 625 timer counts.

Wait Count: The wait count basically denotes the **OFF time of the duty cycle of Triac**.
Half cycle of 50Hz sine wave is of 0.01 seconds duration and it was represented by number of clock pulses in above discussion. Here**, 0.01 second is equal to 625 clock pulses**. **For phase control operation, the Triac remains OFF for certain time duration (OFF time) after the zero-crossing occurs**. Then it remains ON until next zero-crossing of sine-wave occurs (ON time).
Wait count is the Triac OFF time, represented by number of clock pulses that occurs within that time period.

There is a non-linear relationship between this wait count and generated RMS voltage .We have experimentally determined the relationship between timer wait count and generated voltage, and found the empirical cubic equation to use in our further programming (to be discussed in details later). The sample equation and curves are shown below:

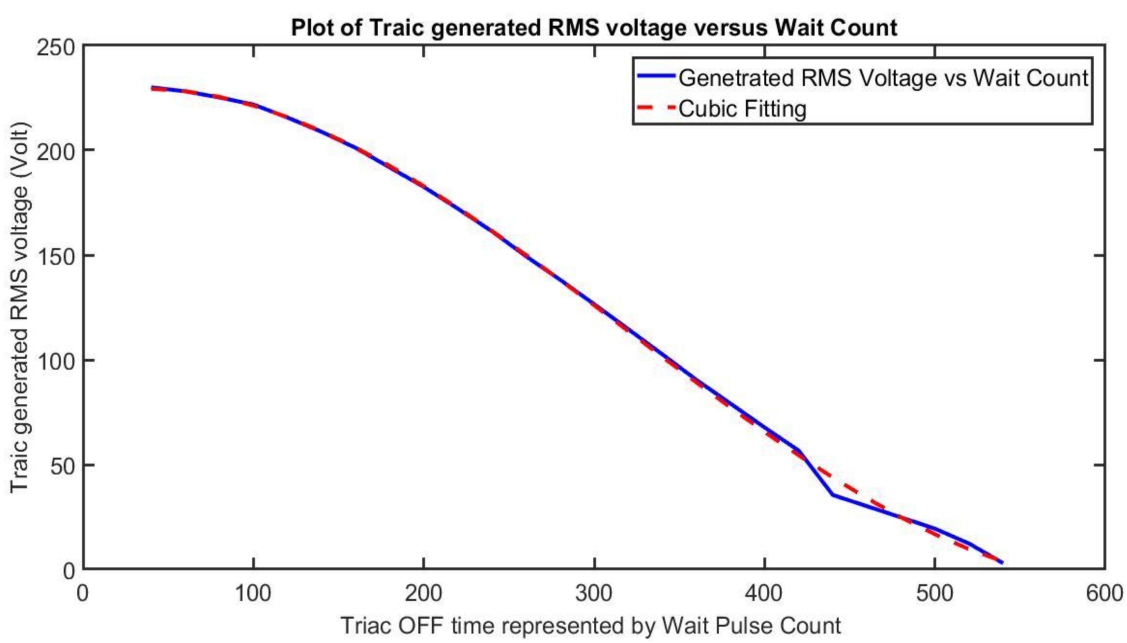


Figure 3.10: plot of RMS voltage output of Triac versus wait pulse count

As we can clearly see, the relation between Triac off time and generated RMS voltage is given by –

$$V_{rms} = 2.4914\times10^{-6}\times T_c^{\,3} + 0.0024\times T_c^{\,2} + 0.1658\times T_c + 226.41$$

Where T_c = timer wait count
And V_{rms} = generated RMS voltage

Steps for Programming:

Step 1: Header files for Arduino mega input/output interrupt operations and I2C operations, that is, avr/io.h , avr/interrupt.h ,avr/wire.h are included.
Step 2: Pins for zero crossing detection, Triac driver pulse output are defined
Step 3: All global variables that are to be used in this piece of code are defined
Step 4: Arduino *setup()* loop is started where,

To set up the I/O pins:-

i) ZCD pin is set as input, and set to HIGH to enable the in-built pull-up resistor for high voltage protection
ii) Triac gate driver pin is set as output

To set-up the components involving in timing sequence generation:-

i) Comparator OCR1A is initialized
ii) TIMSK1 is set to 0×03 to enable comparator OCR1A and interrupts
iii) Timer control registers (TCCR1A and TCCR1B) are set for normal operations.
iv) Interrupt Service Routines (ISR) is defined as *zeroCrossingInterrupt()* and attached at pin 2.
v) Main function of ISR is defined – to start timer TCNT1 from zero, with a 256 frequency divider(done by setting the timer control register TCCR1B = 0×04)
vi) ISR comparator-exceed function is defined – to set the Triac gate drive pin to HIGH(when wait time is exceeded)
vii) ISR overflow-exceed function is defined – to set the Triac gate to LOW(when required ON time is over)
viii) The *setup()* function is over.

Step 5: The *main()* loop which is to be executed periodically until the power is withdrawn from board is defined:-

i) Detection of exterior light and stored into local variable.
ii) External contribution calculated from external Illuminance and saved into another local variable
iii) Target Illuminance value is defined.
iv) Required artificial light needed is calculated by subtracting the external contribution from Target Illuminance and stored into variable.
v) Wait Count is calculated from governing equation
vi) Comparator OCR1A is set to Wait Count .
vii) Pulse width is set to 625- Wait Count (i.e., ON time = total time –OFF time)
viii) A delay of 15 second is applied to check again the external light level.
ix) The *main()* function is now over.

<u>Timing Sequence Algorithm:</u> The timing sequence generation algorithm is presented through a flow chart on next page.

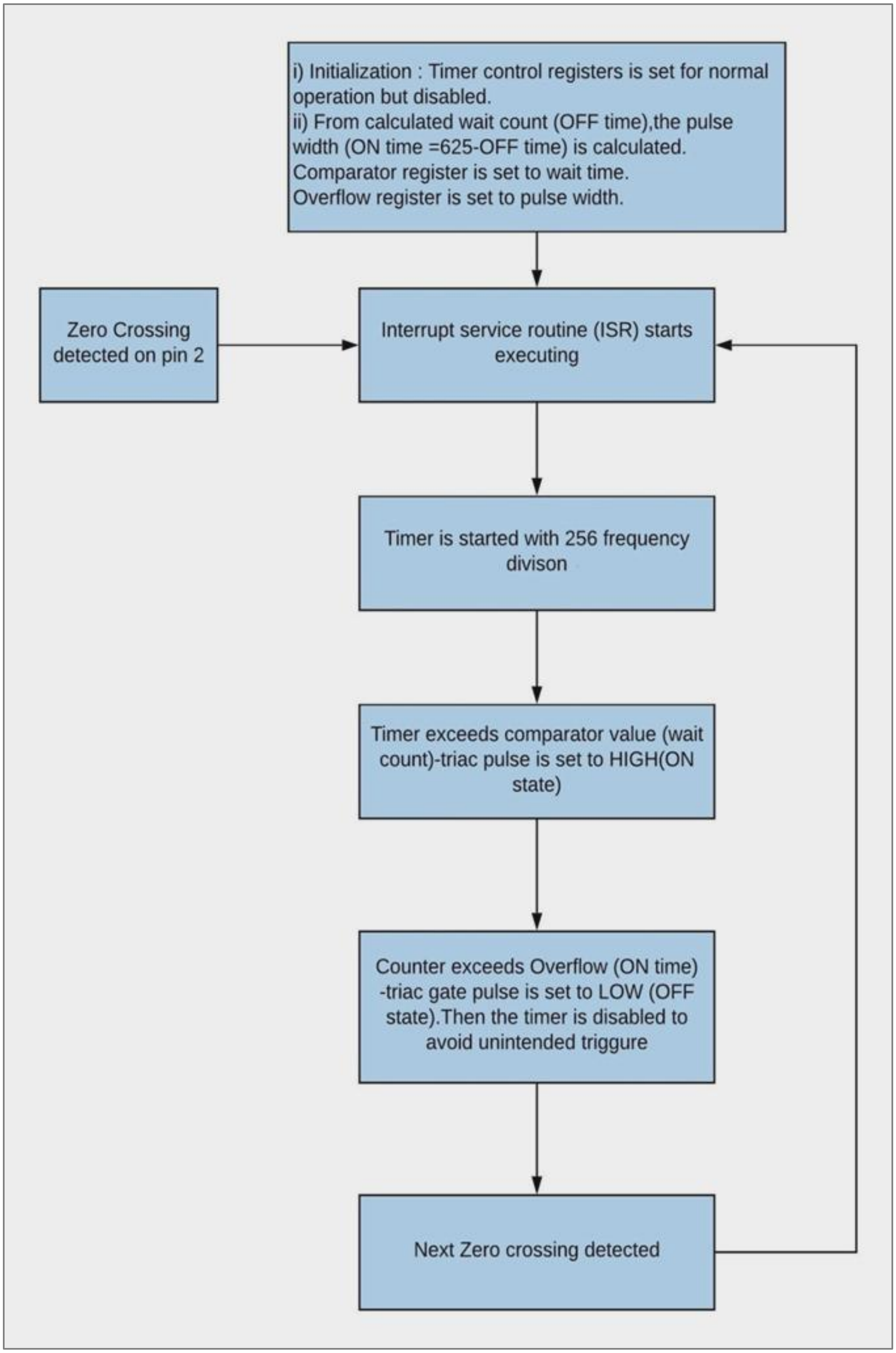


Figure 3.11: Flowchart for timing sequence generation algorithm

3.1.2.4 Triac Based Phase Control

The Triac that has been used here is Q6015L5, which is a 600V, 200A 3-pin bi-directional Triac. This Triac can be triggered from a blocking mode to conduction mode for either polarity of applied voltage and is designed for AC switching and phase control application such as speed control, lighting control and static switching relays. The trigger pulse is applied between the gate pin and MT2 pin of the Triac.

Q6015L5 has been designed to supply a rated load current of 15A.

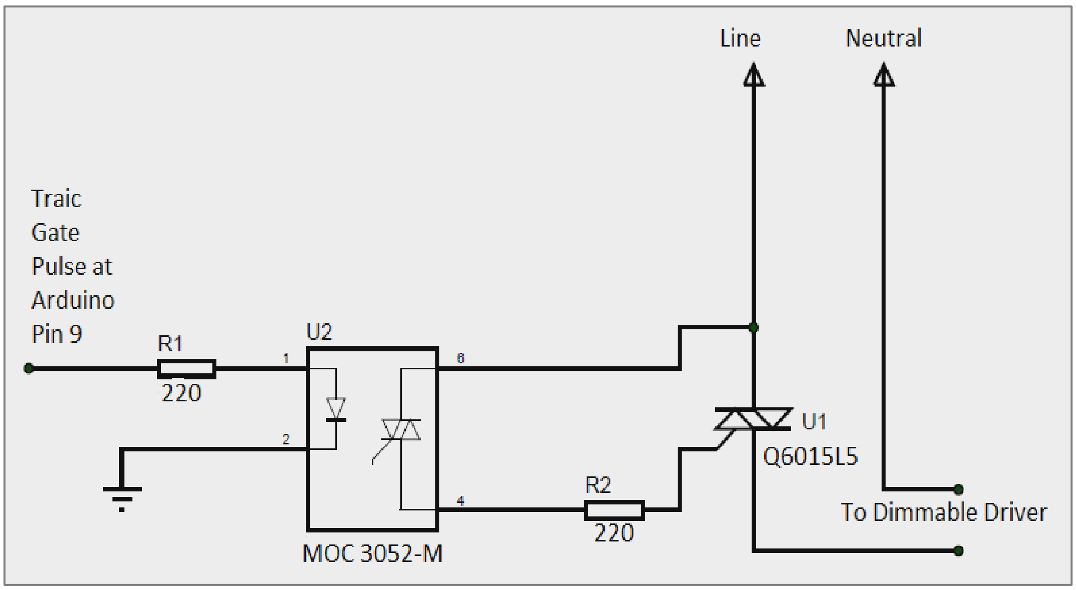


Figure 3.12: phase cutting circuit using opto-isolator and Triac

Opto-isolator MOC 3052-M, 6-Pin DIP random-phase Triac driver has been used here to isolate the high voltage of supply from sensitive control circuits and Arduino.

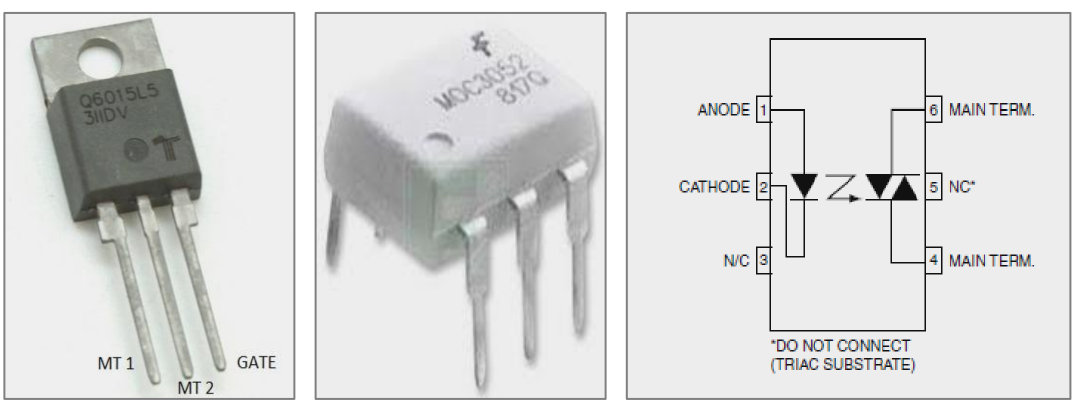


Figure 3.13: Q6015L5component image (Left), MOC-3052-M component image (Centre), and its pin-out diagram (Right)

3.1.2.5 Bill of Materials

The bill of materials of all the components that are used in the overall circuit discussed above is as follows:

Name Of the component	Specification	Quantity	Price in Rupees
TSL-2561	0.1-60,000lx	1	198
H11AA1	Isolation voltage 7500 VAC ; Isolation Resistance 10^{11} ohm	1	45
MOC 3052-M	Isolation voltage 7500 VAC ; Isolation Resistance 10^{11} ohm	1	25
Q6015L5	Rated Blocking Voltage 600 V Rated load current 15A	1	60
RESISTOR	15K ,3W	4	4
	1.5K, 2W	5	5
	220,1W	1	1
Arduino MEGA 2560	-	1	745
Total			1083

Table 3.1: Bill of materials for controller circuit and external light sensor

3.2 LED Luminiare and Dimmable Driver

In this work, LED Panel (Round) developed by SYSKA LED was used, whose specifications are given below-

- Model No : SSK-PA2346E
- Rated Voltage: 15W
- Input Voltage: AC 90-300V,50Hz
- Lumen Output: 930 Lumen
- Operating Temperature: -20° C to 60° C
- CCT: 6500K

The dimmable LED driver that has been used is also developed by SYSKA LED; some of its specification is listed next –

- Model No: SSK-15W-N
- Input Voltage: 200-240V AC,50/60Hz
- Output: 32-45V, 300A
- Power Factor : 0.9 or greater

Figure 3.14: SYSKA SSK-15W-N Dimmable LED Driver, 15W

4. EXPERIMENTAL EVALUATION OF THE PROPOSED SYSTEM

4.1 Set-up for Study the Characteristics of Daylight Pipe

In this section, the set-up for study the light output characteristics of the daylight pipe (DLP) has been discussed in detail. One basic DLP, developed by SKYSHADE, has been installed in one of the room under Illumination engineering Laboratory, Electrical Engineering, Jadavpur University. The room is on the top floor and the collector of the DLP receives unobstructed sunlight entire day. The Dialux simulation of the room is shown below –

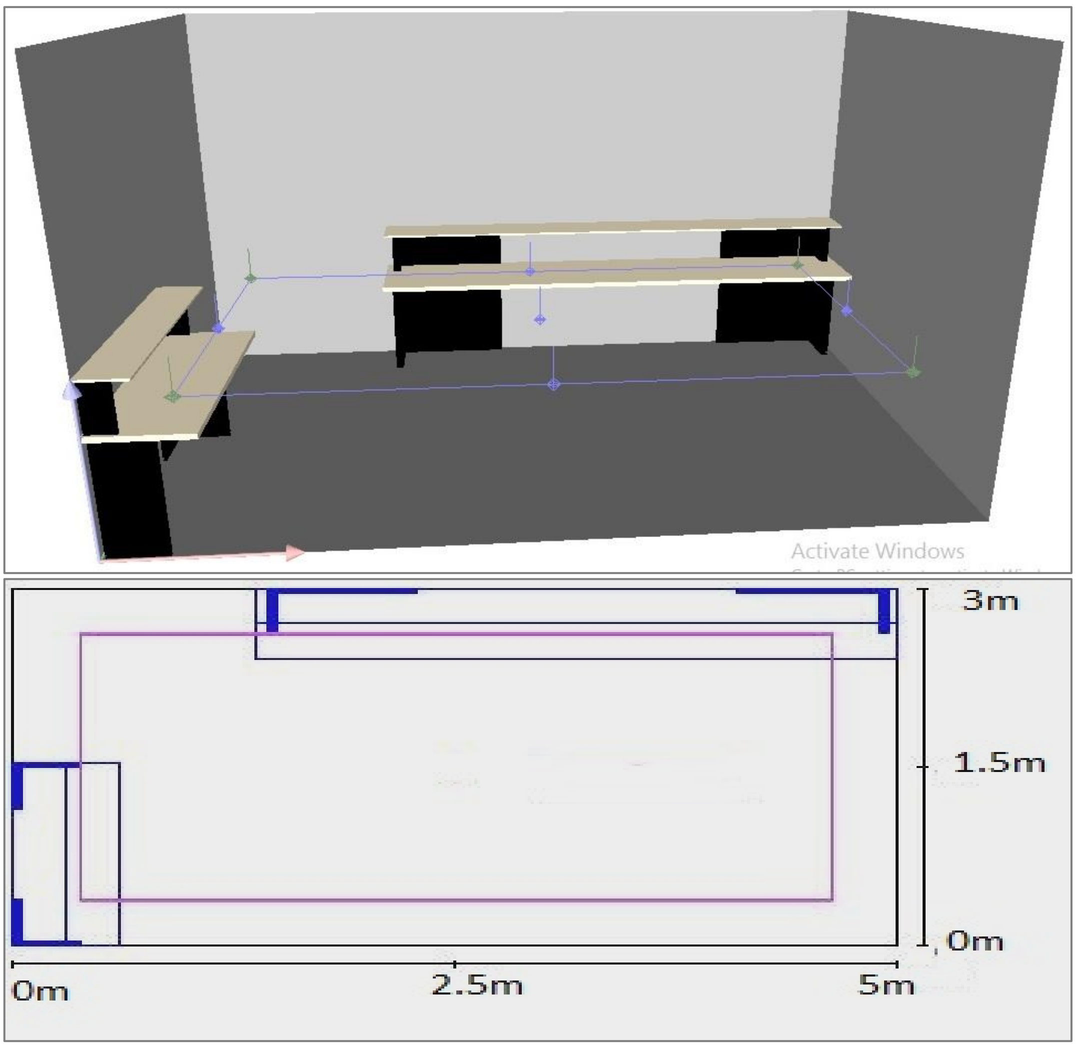


Figure 4.1: Dialux simulation of Room containing DLP and the Lux-meter positions: 3D view (Top) and Floor-plan (Bottom).

Specification and dimension of the room is given below:

- Room dimension : 5m*3m*2.77m
- Position of DLP: Centrally placed at ceiling
- Room surface reflectivity: Ceiling (55%), Wall (3 walls have a reflectivity of 46%, In one wall, blue curtain was used, estimated reflectivity 20%), Floor (28%)
- Luxmeter position: 9 Luxmeters positioned symmetrically in 3 by 3 grid fashion, with a clearance of 0.75meter from wall, at a height 0.8 meter.

To record the light output throughout the day, 9 calibrated luxmeters, developed by ----- was placed at a standard work-plane height of 0.8m. These Luxmeters were calibrated by Bench Photometer method, against a CL-200A Luxmeter. The luxmeters were placed uniformly throughout in the room as shown in the figure. These Luxmeters can produce both digital analog outputs. Also, one luxmeter was placed on the roof to measure the external Lux level.

To record these analog data, a 16-channel Data logger, developed by AGILIENT, was used. The Data-logger records the data from 9 AM to 5 PM, at an interval of 30 seconds. This was done to detect the daylight variation, both interior and exterior, throughout the entire day. Readings were taken discretely in the month September-November, 2018.

The specification details of Luxmeter and data-logger used, could be found on annexure section.

4.2 Set-up for Testing the Proposed Controller

The working of entire system has been discussed thoroughly in previous section. Since the accuracy and validity of discussed theory depends upon successful and accurate operation of each component, each part must be tested individually to ensure correct operation. The testing process of the proposed controller can be divided into some discrete steps, where each and every sub-components of the system is tested individually. These steps are -

- Calibration and testing of external light sensor
- Testing of Zero crossing detector using oscilloscope
- Generation of Triac gate driving pulse with changing the wait count
- Generation of controlled voltage and required dimming with change in Triac duty cycle.

And lastly, I have tried to provide and test the integration of the control system with daylight pipe in simulated environment.

Some aspects that are common in entire testing process are listed below-

- Entire process was done in light-controlled environment, that is, without any unwanted/stray light intervention. Illumination engineering dark laboratory provided such environment.
- HP laptop was used for coding purpose of Arduino microcontroller, as well as a power supply for the Arduino using USB cable.
- Isolation transformer was used in entire process, to ensure safety of electrical units.

4.2.1 Calibration of External Light Sensor :

TSL-2561 external light sensor was calibrated against CL-200A Luxmeter. Both CL-200A meter and light sensor was placed under a 100W GLS lamp, developed by Philips, at a height of 0.75 meter. So, in the absence of other stray light, only direct component of lamp generated light was incident on the sensors. The supply voltage to the tungsten filament lamp was varied from 110V to 220V.For each TSL-2561 reading of 20lx-400lx, at a step of 20lx, readings of CL-200A were measured. The TSL-2561 was connected to Arduino as seen in figure-, for sake of measurement. The calibration result is shown below -

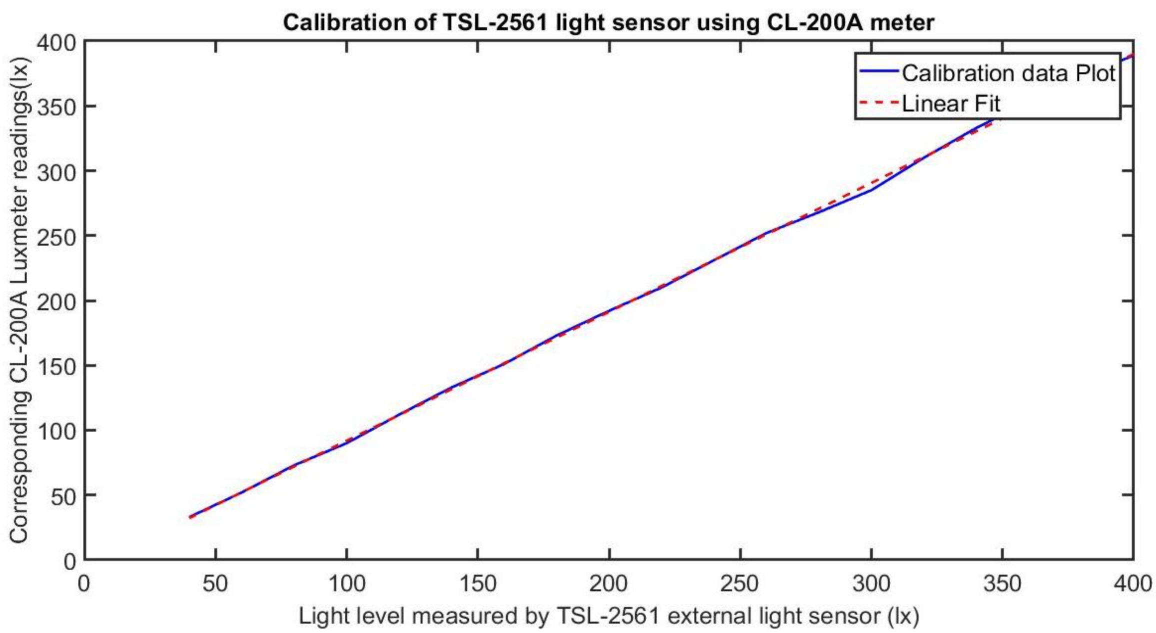


Figure 4.2: Plot of TSL-2561 sensor reading versus standard luxmeter reading. Blue line shows the direct plot, while Red dotted line indicates the nature of linear fit between them.

The relationship between these two can be represented by the linear equation given below –

$$\text{Actual Lux level} = 0.9937*(\text{Lux measured by TSL-2561}) - 7.4526$$

This relationship will be used for further experiments.

4.2.2 Testing of Zero Crossing Detector Using Oscilloscope

In section 3, entire functionality of zero crossing detection has been discussed in detail. Clearly, whenever there is any supply voltage (any polarity) between opto-coupler's pin-1 and pin-2, light is emitted. So the transistor keeps conducting the pin-2's +5 Volt to ground. Only when the supply sin-wave crosses zero, the transistor gets open-circuited, and a narrow peak is obtained in pin-2. That's how Arduino detects the zero crossing.

To test this above scenario in oscilloscope, the partial circuit looks like below-

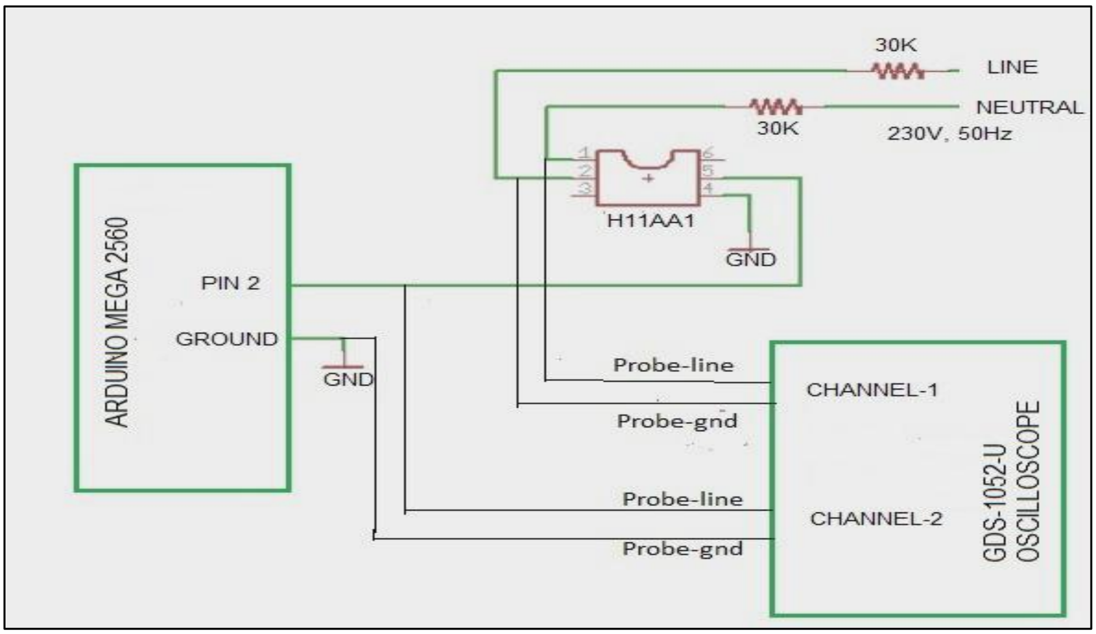


Figure 4.3: Representative partial circuit diagram for testing the zero crossing detector waveform by oscilloscope.

Clearly, we should expect a momentary peak on channel 2, every-when channel-1's supply sine-wave crosses zero. The oscilloscope outcomes are shown in next page.

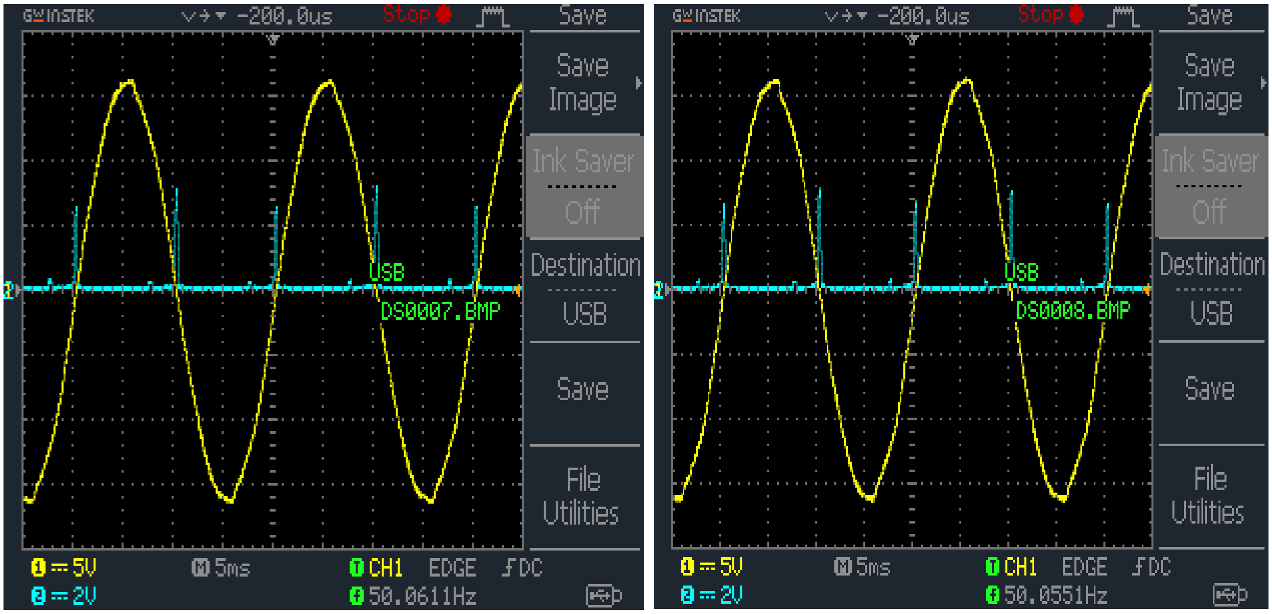


Figure 4.4: Obtained waveform of supply (at Channel 1: Shown with Yellow color) and zero crossing detection pin-2 voltage momentary peak(at channel 2: Shown with Blue color), at two separate instance(Left & Right)

So the ZCD functionality can accurately detect the zero crossing, which is used to perfectly time the phase cut of the sine-wave, and generate controlled supply voltage for the driver. For each voltage peak at pin-2, an interrupt is generated, which informs the microcontroller that sin-wave has crossed zero, and thus times the duty-cycle of Triac.

4.2.3 Generation of Triac Gate Driving Pulse as per Required Dimming Level

The duty cycle of Triac is changed to vary the dimmable driver input voltage, and subsequently vary the dimming of LED units. From daylight availability information, the required artificial light dimming level is calculated. For the required dimming level, the duty cycle of Triac is obtained. The OFF time/wait count of Triac determines the output voltage of Triac. These processes have been discussed in section 3, in details.

Here, we test whether the program generated duty cycle can produce required Triac gate driving pulse or not.

Now for Q6015L5 Triac, with basic 15W tungsten filament lamp as load, the gate driving pulse is measured with oscilloscope. Below figure depicts the required circuit-

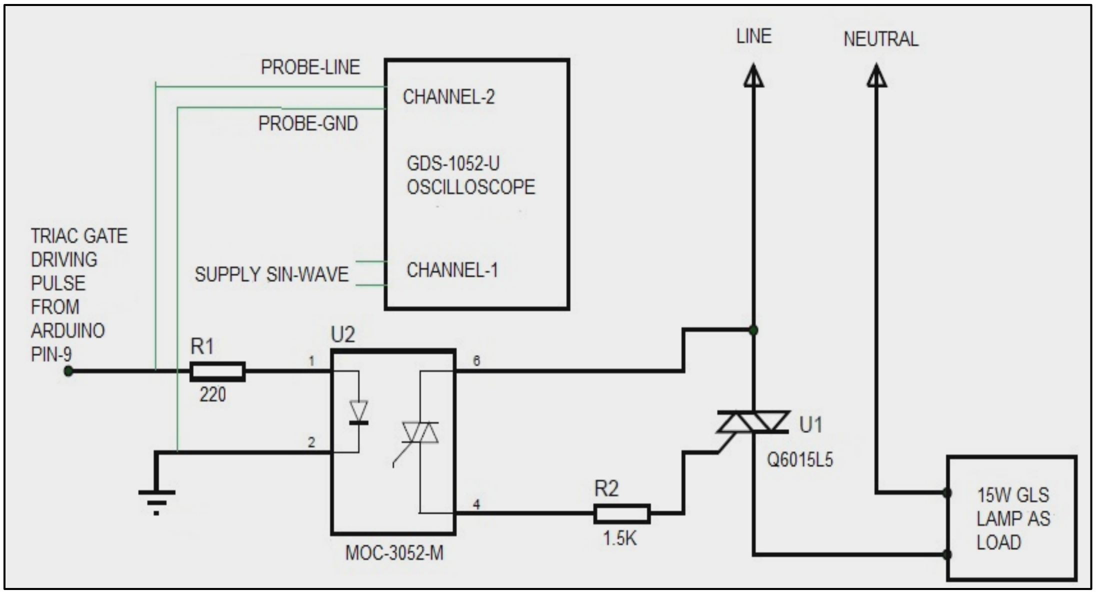


Figure 4.5: Testing of Triac gate pulse generation with change in duty cycle by Arduino and as viewed by oscilloscope for 15W tungsten filament lamp.

The time taken by entire half sin wave can be represented 625 clock counts as shown in 3.1.2.4 sub-section. The OFF time/wait count is varied and the Triac gate pulse generated by Pin-9 is measured with respect to supply waveform. Here, the measurement for wait count 100, 200, and 450 has been shown in next page.

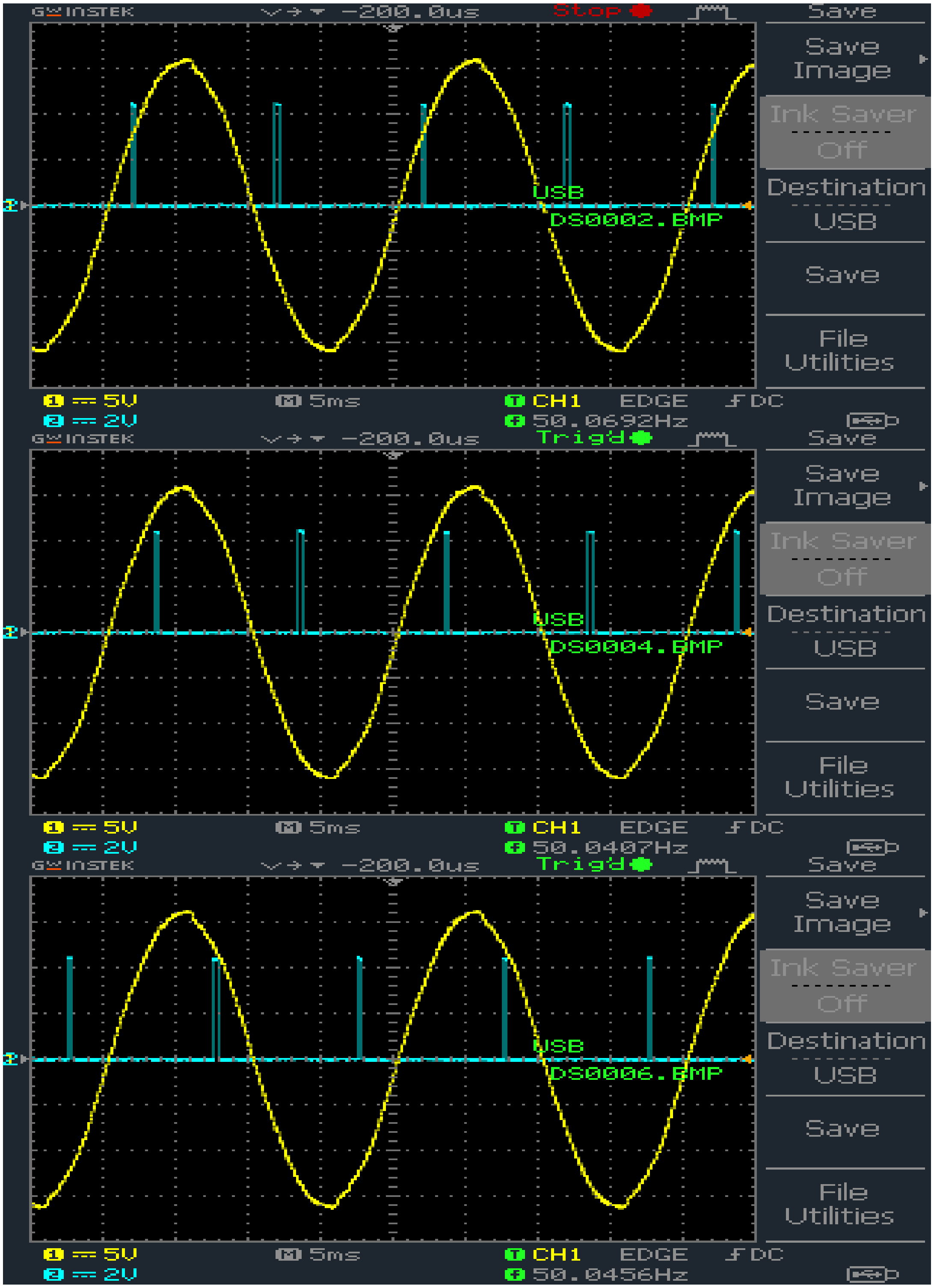


Figure 4.6: Triac gate driving pulse generated by pin-9 of Arduino(shown with Blue color) with respect to supply sine wave(shown with Yellow color), for Off time/wait count 100(Top), 200(middle) and 450(Bottom) ; the half sine wave is of 625 clock counts

4.3 Variation of Light Output of 15W SYSKA LED with Change in Phase-Cut RMS Supply Voltage

The light output of LED should vary when the supply voltage to its dimmable driver is changed with phase controlled variable supply. The RMS voltage level of phase controlled supply depends upon the duty cycle (and hence the OFF time or wait count) of the Triac.

Since the measurement of Lumen output of the lamp is complex and requires delicate instrument set-up, we avoided the measurement of total Lumen output with change in supply RMS voltage. Again, the change of lumen output and hence the dimming of the LED can be represented by the change of direct horizontal illuminance on a work-plane directly under the LED, situated at a certain perpendicular distance from lamp. So, in our case, the variation of light output is measured in terms of change in horizontal direct illuminance available at a certain distance from the LED, while the phase-cut supply voltage is varied through the change in wait count(OFF time) of the Triac.

To test this, the LED lamp was placed on a stand facing vertically downward, and the luxmeter was placed at a distance 0.93 meter on a horizontal plane. To avoid indirect/reflected components and stray light, entire experiment was done in a light-controlled environment of the dark room, with all other light kept OFF.

The wait count (representing the OFF time) was varied from 20 to 560, at a step of 20.(It was discussed earlier that total half-sine wave is represented by 625 clock counts; see sub-section 3.1.2.3 and 3.1.2.4).The change in output RMS voltage is measured for each step, by a multi-meter, connected across the Triac(or the input stage of the driver).The direct horizontal illuminance was measured by luxmeter for all the steps.

This process was repeated multiple times with changing step size to get a good average reading. The readings were plotted and linear/cubic functions representing the relationships, were generated by MATLAB.

The sample plots generated by one set of reading are shown in next page.

a) Plot of RMS voltage generated by the Triac versus Wait Count applied:

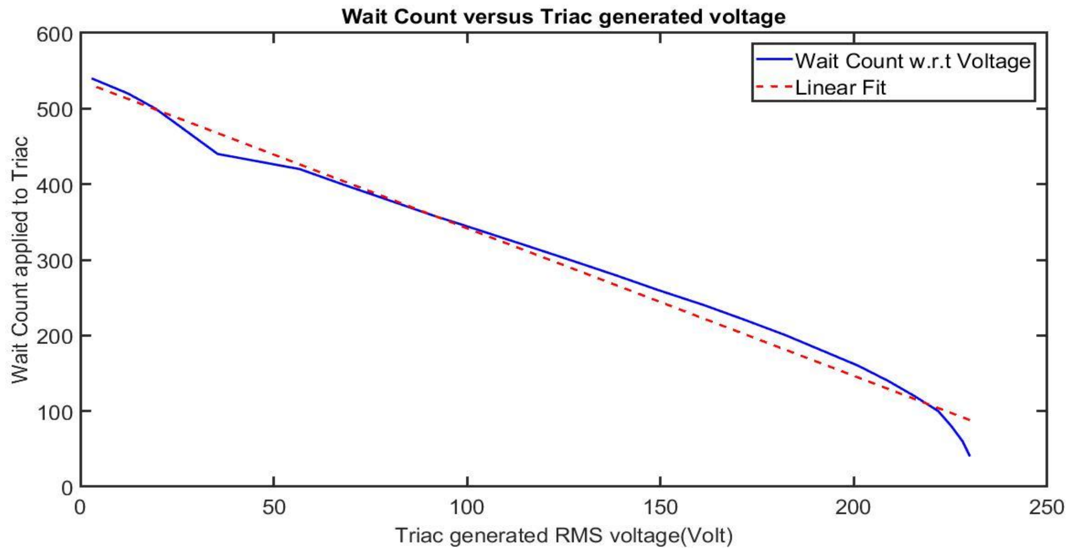


Figure 4.7: MATLAB Plot of Wait Count applied to Triac versus RMS voltage generated

The linear fit was generated by MATLAB. The governing linear equation describing relation between Wait Count (Tc) and generated voltage (Vrms) is shown below:

$$Tc = -1.951 * Vrms + 536.77$$

b) Plot of Lux level obtained at a distance 0.93meter directly below the LED versus Wait Count applied:

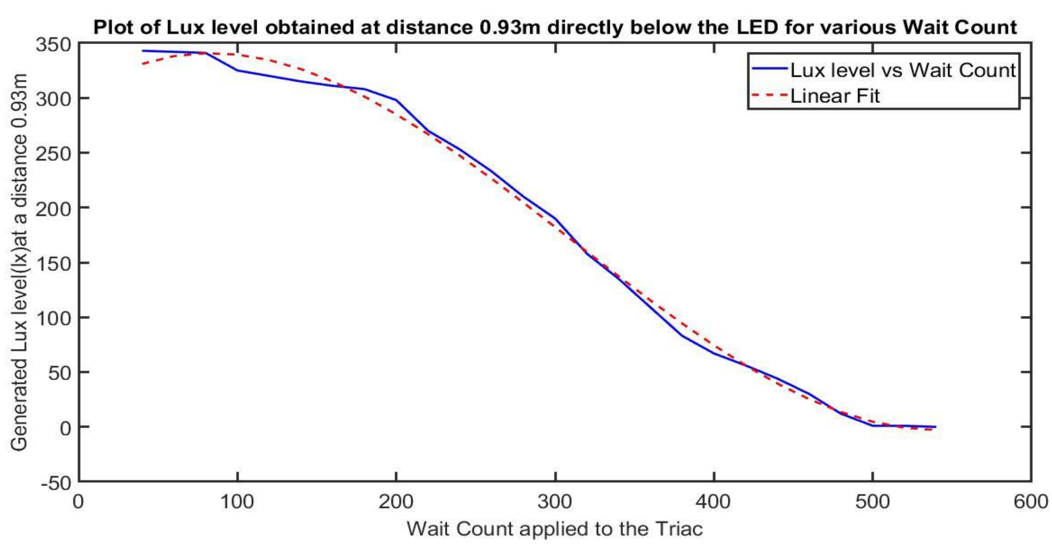


Figure 4.8: MATLAB Plot of Lux level obtained at a distance 0.93m directly below the LED versus Wait Count applied

The cubic fit was generated by MATLAB. The governing linear equation describing relation between wait count (T_c) and Lux level(E_h) is shown below:

$$E_h = 7.203710^{-06} \text{ X } T_c^3 - 0.0067 \text{ X } T_c^2 + 0.9718 \text{ X } T_c + 302.47$$

c) Plot of RMS voltage at Triac output versus Lux level obtained at a distance 0.93meter directly below the LED:

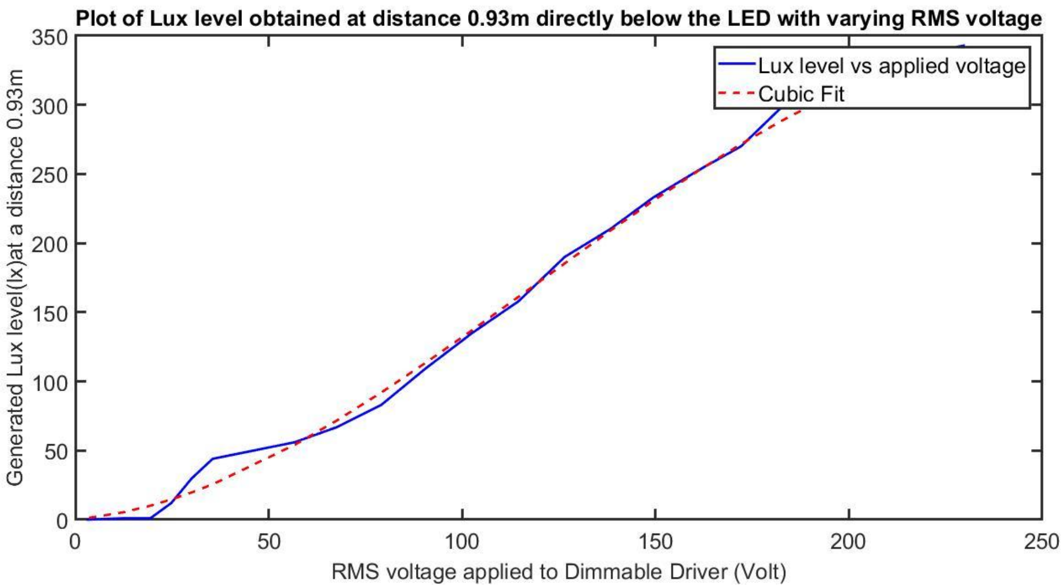


Figure 4.9: MATLAB plot of Lux level obtained at a distance 0.93meter directly below the LED versus RMS voltage applied to Dimmable Driver

The cubic fit was generated by MATLAB. The governing linear equation describing relation between applied RMS voltage (V_{rms}) and Lux level (E_h) is shown below:

$$E_h = 7.203710^{-06} \text{ X } V_{rms}^3 - 0.0067 \text{ X } V_{rms}^2 + 0.9718 \text{ X } V_{rms} + 302.47$$

- In this part of experiment, it was observed that while voltage decreasing, the light gets to OFF state from ON state at a RMS voltage at around 24 volt (approximate average)

4.4 Testing of the Proposed Controller with Time-Varying Daylight Data

As discussed earlier, the main purpose of any artificial light controller is to provide a fixed amount of average illuminance at the work-plane with random variation of available daylight level throughout the day. This fixed amount of average illuminance needed in the work-plane, is termed as Target Illuminance. And the amount of artificial light required is the difference between target illuminance and available daylight at the work-plane. So, for a given daylight availability, the controller must produce the required dimming level of artificial lights.

For this experiment, I have used the external daylight data reading measured by Li-COR Li-250A light meter, which took external lx level at the rooftop continuously on the day of 10/06/2018. This data was stored in Data-logger with a time interval of 30 seconds. The variation of daylight level between 11 AM to 12 PM was considered for use.

Now, clearly, by observing the property of light transfer of daylight pipe (DLP), It can be safely assumed that the daylight available at work-plane directly below the DLP, varies linearly with external daylight, and its only gets scaled down by a certain factor depending upon light transfer capability of DLP and work-plane height.

The approximated scaling factor was taken as 0.003, i.e. only 0.3% of external light level is available on the work-plane, inside the room interior.

So, from above daylight availability, the Arduino microcontroller must calculate the required level of artificial light. To generate that amount of artificial light, the required duty cycle (OFF time/wait count) must be calculated.

Now, in previous subsection(Sub section 4.3 b)), the relationship between Lux level obtained at a distance 0.93 meter directly below the LED versus Wait Count applied is obtained. Reversly, for a desired Lux level at a distance 0.93 meter directly below the LED, the wait count can be obtained from the same data previously used. If same data used in Figure , is plotted with its axes interchanged, the required Wait Count can be found. This relationship is shown below-

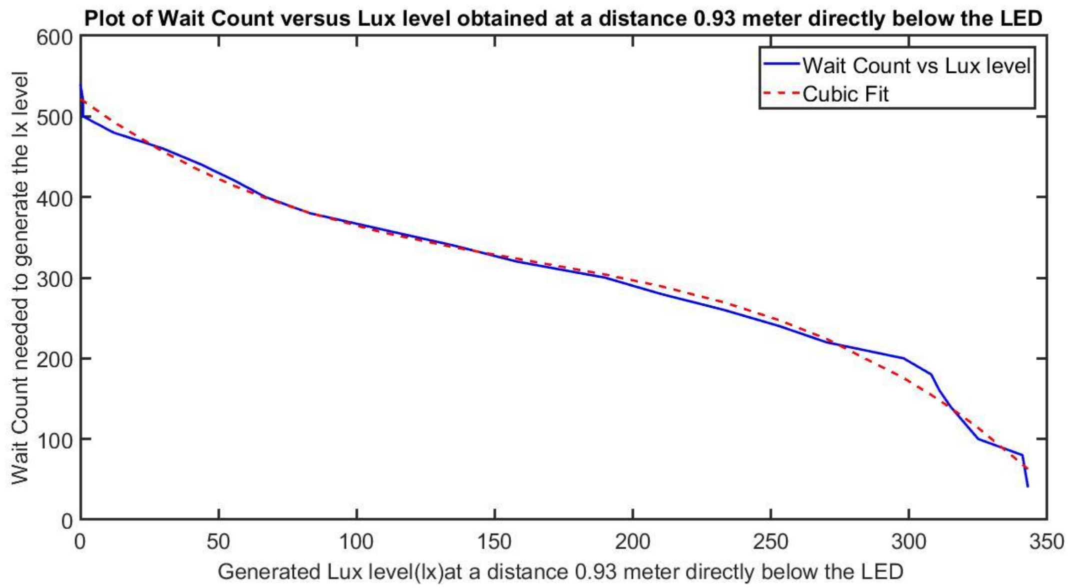


Figure 4.10: MATLAB Plot of Wait Count applied versus Lux level generated by that wait count at a distance 0.93meter directly below the LED

The cubic fit was generated by MATLAB. The governing linear equation describing relation between Lux level generated (E_h) versus wait count (T_c) needed to generate that lx level and is shown below:

$$T_C = -2.4904 \times 10^{-05} \times E_h^{\,3} - 0.0120 \times E_h^{\,2} - 2.5532 \times E_h + 521.97$$

So the functional steps for this experiment are-

i. External daylight data for 10/6/2018, between 11 AM to 12 PM, at an interval of 30 seconds were taken as sample data representing the daylight variation.
ii. This data was scaled to obtain approximate daylight available at work-plane situated in room interior, with a scaling factor of 0.5%.
iii. Target Illuminance was taken as 350 lx.
iv. Artificial light needed to achieve target illuminance was calculated by subtracting the daylight availability data from target illuminance.
v. Wait count (representing duty cycle) required to generate that artificial light calculated from above relationship(developed by plot in Figure)
vi. The wait count is fed to the Triac to generate required dimming of LED.

Now, the relationship between Lux level generated (E_h) and wait count (T_c) needed to generate that lx level(Figure) was only valid for the same setup as used for developing the data for Figure ,Same setup had been used for this experiment also. So the LED lamp was hung on a stand facing vertically downwards, and the luxmeter used for measure the Lux level was placed at a distance 0.93 meter directly below the lamp.

The daylight data was hardcoded/stored in microcontroller and for each 30 second's data, generated artificial light level was measured. All these measurements are shown as graphs below –

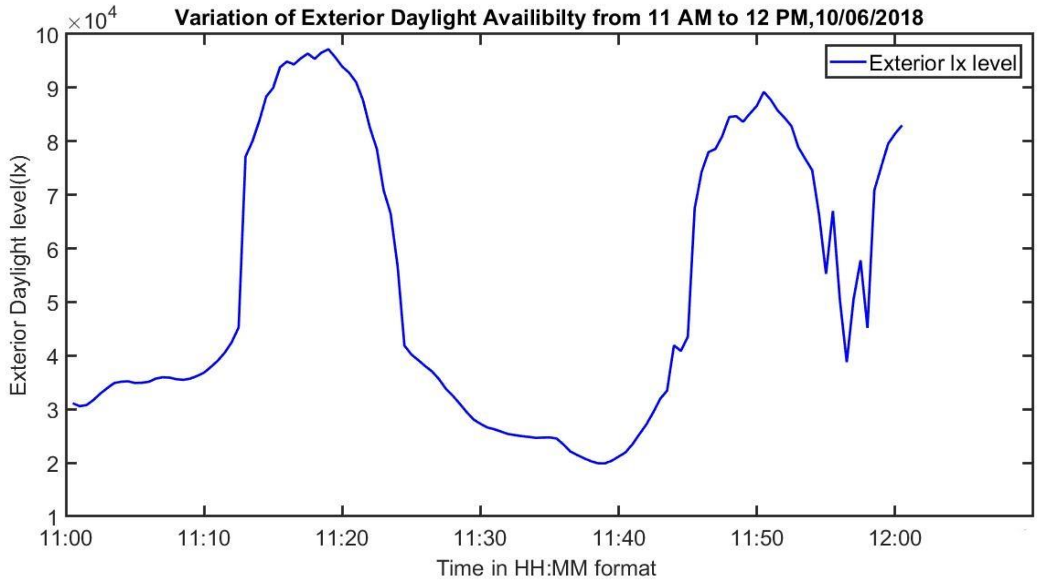


Figure 4.11: Plot of Variation of external daylight level (reading taken at an interval of 30 seconds) with respect to time between 11 AM to 12 PM on 10/6/2018.

So, on that day (depending on cloud cover), the daylight amount varied largely, between 20K to 95K Lux within one hour.

The total result of this experiment was represented graphically in next page.

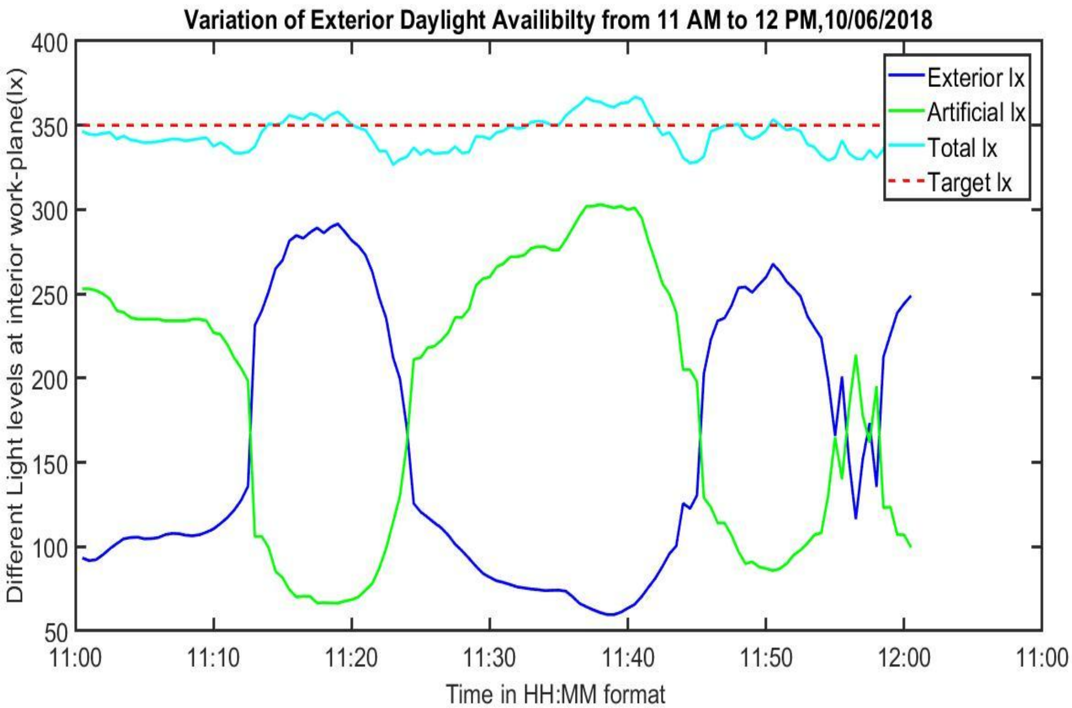


Figure 4.12: MATLAB plot showing time-variation of daylight level at room interior work-plane and controller generated artificial light level during that time. Time is shown with HH:MM:SS format with an interval of 10 Minutes from 11 AM to 12 PM, on X-Axis. On Y-Axis Different Lux level has been shown as follows: a) GREEN line represents daylight available on the work-plane at that particular time; b) BLUE line represents real-time, controller generated Lux level on the work-plane; c) MAGENTA line shows total available light level at any particular time; and d) RED line shows the target illuminance level, which had been considered as 350lx

Clearly from figure 4.12, there is a difference between target illuminance (shown by RED line) and total (daylight + generated artificial light) lx level (shown by MAGENTA line) , which means the controller generates overshoots and undershoots with respect to the target illuminance. Although, it is not a huge difference, but it should be taken under consideration and improve/upgrade the performance of the entire system. The deviation in the case is shown below:

- Maximum undershoot(difference of target and generated minimum light level) is 23.3635lx
- Maximum overshoot(difference between target and generated maximum light level) is 16.8587 lx
- Standard deviation of generated light level from target is 11.1013 lx

This experiment was done using different scaling factors (ratio of work-plane illuminance generated by DLP and external daylight level), and similar results were obtained.

4.5 Testing of Integrated System:

In previous case, we have tested whether the target illuminance at a point on the work-plane can be supplied by proposed system or not. And it has been successfully shown that, the controller can generate required artificial light level to provide the target illuminance, according to time-varying daylight availability.

But to integrate this controller in a room, lit with multiple LED's, it is needed to consider some other aspects for successful operation.

From the integration point of view, the factors, that must be taken into account are-

i. Previously, only the control of one isolated LED was considered. But in real life scenario, multiple LED's are used inside a room, depending upon the room size and target illuminance.
ii. In previous case, only point-specific illuminance was considered. But for integration in real-life, average illuminance throughout the room, as well as uniformity must be taken into account.
iii. Previously, only direct component of light (both for artificial and daylight) was considered. But in interior lighting, the reflected/indirect components of light must be taken into account, without which the lighting design is meaningless. Room surface reflectivity's plays a vital role in this calculation.

To address these considerations, a new approach was taken; where,

i. A room was considered, where multiple LED's are used to simple provide the target illuminance. The LED's can generate targeted illuminance level and uniformity at night-time, i.e., without daylight contribution. These multiple LED's (or LED control groups) can be controlled by a single unit of Arduino microcontroller, thus decreasing the overall cost of the control system.
ii. Instead of point-specific illuminance calculation, to find light level at entire room, only average daylight availability and average artificial light level were considered. It was also made sure that the overall uniformity produced by the system, was always above standard design value of 0.7.
iii. To consider the reflected light components of artificial light, Dialux simulation of the room was used. In the simulation, the actual room dimensions and the actual reflectivity of all room surfaces in the room was considered.

Due to lack of logistics and time, above mentioned experiment could not be performed in real room environment. The room shown in figure 4.1, was used to simulate the environment under different artificial lighting conditions.

The procedural steps for this experiment are-

i. Room shown in figure 4.1, was simulated in Dialux with real-valued room dimensions and surface reflectivity.

ii. 8 LED lamps were used in simulation, to provide the targeted 500 lx at work-plane. These luminiare can provide the targeted illuminance and uniformity when lit at 100% ON state, to supply the target illuminance at night-time, without the presence of daylight.

iii. The lamps were classified into three control groups with respect to their spatial position inside the room. Lamp positions were symmetric with respect to DLP's diffuser outlet.

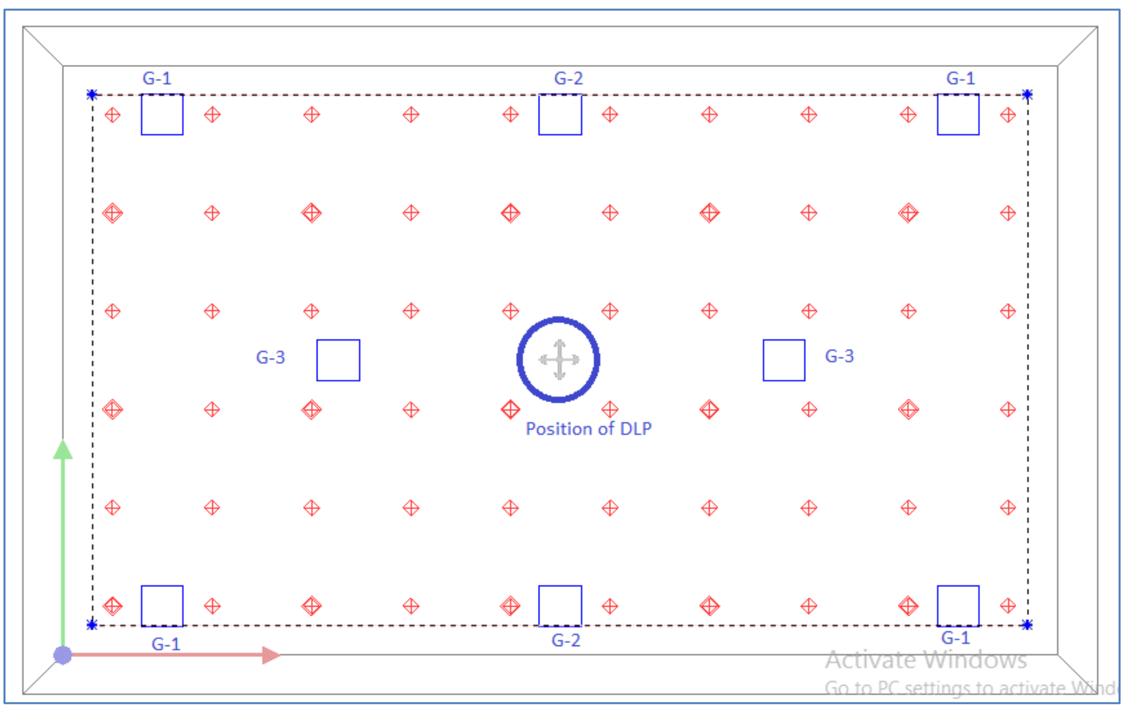


Figure 4.13: Position of lamps under different control groups, Corner lamps are under Group G-1, Two-wall-sided lamps are under group G-2, and two centrally aligned lamps are under group G-3

iv. For all three control groups, the dimming levels (namely d1, d2, d3) were varied from 20% to 100%, at a step of 20%.For all combinations of dimming level (d1, d2, d3), the average artificial Lux level and uniformity was calculated in DIALUX.

Name of Control Group	Position in the room	Dimming level
G-1	4 Lamps situated in the corner	d1
G-2	2 Lamps situated in wall-side	d2
G-3	2 Centrally aligned lamps	d3

Table 4.1: Different control groups used and their position

v. So, for each possible combination of dimming level, average illuminance and uniformity could be found. A look-up table was constructed which contained average Lux level and uniformity for all combinations of dimming levels of three control groups.

vi. For a given value of average daylight availability, required artificial light level was calculated by subtracting daylight contribution from target illuminance.

vii. For this required artificial light, the dimming values of three control groups can be found from look-up table.

To capture the variation of daylight level throughout the day, the daylight data of 10/06/2018 was again considered and 16 readings of external data were taken at an interval of 30 minutes. So this set of data represents the daylight variation from 9 AM to 5 PM.

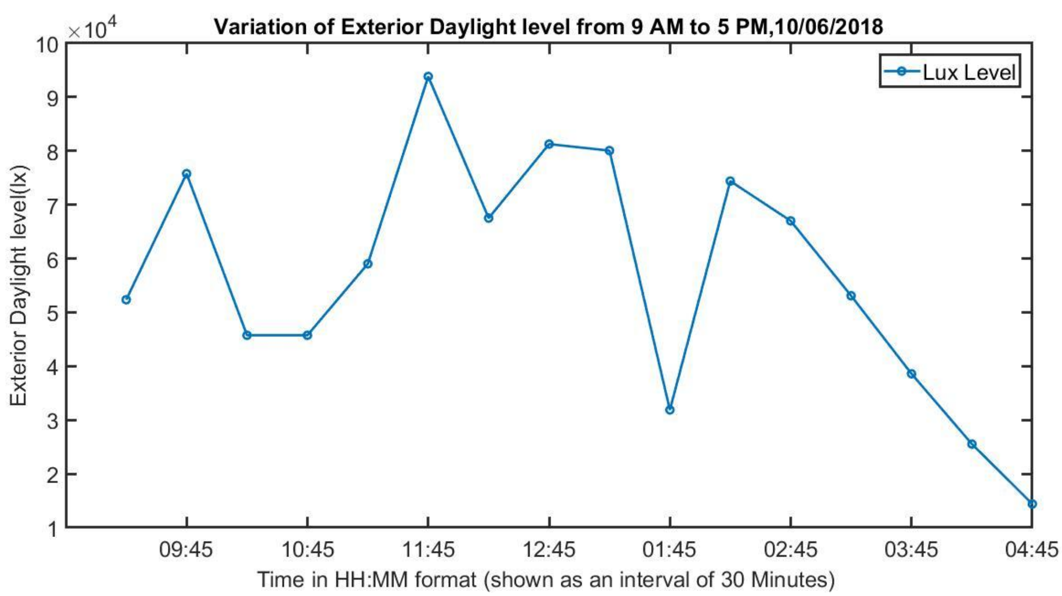


Figure 4.14: Variation of external daylight availability throughout the day of 10/06/2018

This daylight data was scaled by 0.3% and recreated by using a 100 Watt Tungsten lamp. TSL-2561 calibrated external daylight sensor was placed at a distance 0.5 meter from the lamp and required daylight was generated on the sensor plane. So the scaled daylight level was sensed by the calibrated sensor and sensor sent the digital data to the microcontroller.

Using this sensor provided daylight level, the required artificial light level was calculated in microcontroller. (Here the target illuminance was considered as 500 lx). As per the artificial light requirement, the dimming values (d1, d2, d3) of three control groups were approximated from the look-up table. This approximation was done in such way that the predicted dimming values also could generate maximum uniformity of light, as well as average illuminance.

Since three different LED lamps, representing three control groups, could not be used due to logistical problems, only one LED was used. The SYSKA LED lamp was hung from a stand, facing vertically downward. The luxmeter used for measuring the dimmed light output was placed at a distance of 0.5 meter, facing vertically upward and directly below the LED lamp. In this case, when LED dimming level was 100% (Full ON state), the luxmeter measured a maximum value of 505 lx.

For one set of daylight data with 16 readings, dimming level d1 was calculated for each reading. The dimming percentage for d1, was then fed to the LED lamp. By measuring the LED light output with Luxmeter, it was tested whether the predicted dimming percentage was actually produced by the LED lamp or not.

Next, for the same set of daylight data with 16 readings, dimming level d2 and d3 was calculated for each reading. Similar to the case of d1, predicted values of d2 and d3 was also fed to the lamp, and the light output of the lamp was measured. The findings of the experiment is represented by the graphs below-

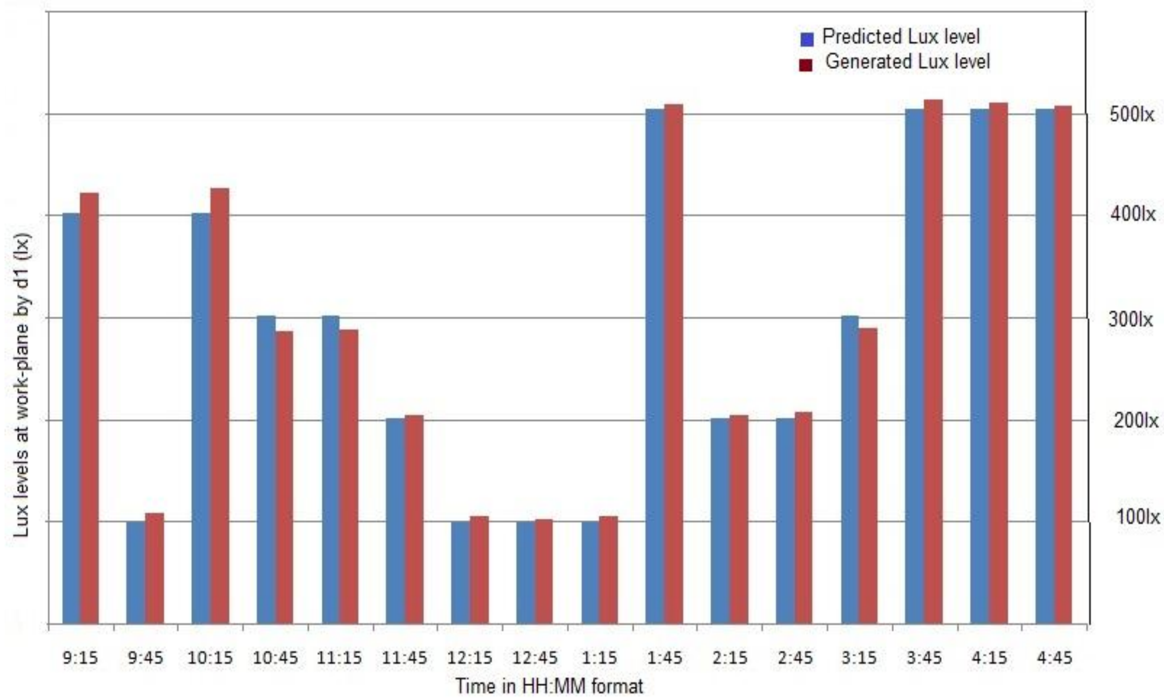


Figure 4.15: Bar plot showing the predicted artificial light level and System generated Lux level for dimming level d1

Form above bar plot, it can be seen that the system generated artificial light dimming values, closely follows the predicted Lux level, which was predicted from DIALUX simulation look-up table. Similar results were found for dimming level d2 and d3.

5. CONCLUSION AND FUTURE SCOPE

In this work, an automated, real-time open-loop control system for DLP integrated LED based indoor lighting system has been proposed, designed and developed. The developed system is used in a room where daylight pipe (made by SKYSHADE, with length 1.2 meter and diameter 0.3 meter) has been used for providing daylight. The developed system is meant to provide controlled supply voltage to the dimmable driver (SSK-15W-N) manufactured for SYSKA LED. The performance of the DLP and the light controller is evaluated in simulated daylight environment and following observations were made -

- Light output of said DLP is almost linearly related to external daylight level
- Light-to-digital converter TSL-2561 can reliably sense ambient light level with minor calibrations and provide the light level data digitally for modern digital controllers.
- Zero-Crossing Detection circuit and logic, used for supply voltage phase-cutting purpose produces intended results accurately, confirmed through waveform measurements by Oscilloscope.
- System can provide Triac gate driving pulse to generate any duty cycle for Triac and hence can generate required supply voltage, without error.
- The dimming level of SYSKA LED used, is closely co-related with phase-cut supply voltage, applied to its dimmable driver. The relationship can be represented as a cubic equation; with high value of co-relation(R-squared = 0.09974)
- For an isolated system containing only one LED lamp, the system can generate the artificial light level required as per daylight availability; and thus can provide the target illuminance level at work-plane. The maximum deviation between target illuminance and generated total light level was found to be 23.6335 lx, and the standard deviation in this case was 11.1013 lx, for a target illuminance of 350 lx

In future, some aspects of entire discourse can be revisited and upgraded strategies and logics can be implemented.

- To study the light output characteristics of DLP, total Lumen output measurement could be performed.
- Prediction of light output characteristics of DLP may be done for numerous sun and sky conditions; for this, Perez model for estimating daylight availability may be considered
- Various numerical models has been already (especially after 2008) developed to integrate daylight with artificial lighting. These models can be studied to find a cost-effective and most reliable process for integration purpose.
- The Arduino based system may be connected with world wide web(www), to provide total remote control of user
- The possibility of integration of proposed system with existing Building Management System(BMS) can also be studied
- Energy saving studies is not presented in this work. This is a huge area where further works can be done.

To conclude, it can be safely asserted that the proposed system is a cheap and reliable option for daylight pipe (DLP) integration with LED based indoor lighting system.

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7. ANNEXURE

Annexure A: Instruments Used for the Experiments

The Arduino programs were written on **ARDUINO IDE 1.8.7**, which is an integrated development environment for cross-platform application (Windows, Linux, Mac-OS), and used for write, compile and burn the code into Arduino device. The programming languages supported by it are C and C++.All the equations and plots shown in this study was derived using **MATLAB 9.3: R 2017b**.Lighting simulations were done by **DIALUX 4.13**.Some of the electronic circuits estimation and sketches were done using **PROTEUS 8** software.
A number of hardware instruments were required for the measurement and also for certain observations. The instruments that were not discussed in earlier sections have been listed below.

1. GW INSTEK GDS-1052-U Digital Storage Oscilloscope :

Oscilloscope was used to check/measure various waveforms generated by Arduino phase cutting mechanism. Output waveform of ZCD and Triac gate driver pins were particularly measured by oscilloscope.

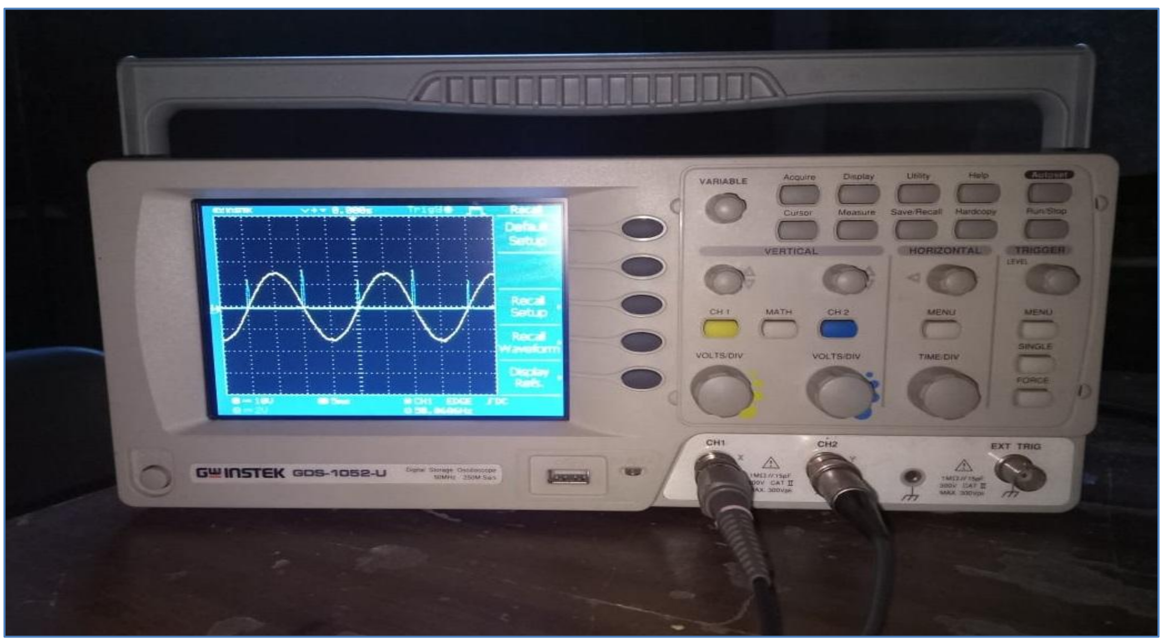

Figure7.1: GW INSTEK GDS-1052-U Digital Storage Oscilloscope

Some technical specifications of GDS-1052-U unit are given below-

- Model No: GDS-1052-U
- Bandwidth: 50MHz
- Display Device: 5.7'' TFT color LCD
- Sample Rate: 250M Sa/S (Real Time Sampling) & 25G Sa/S (Equivalent Time Sampling) (Sa/S= Samples per seconds)
- Number of channels: 2
- Input Voltage: 90V-264V ACRMS
- Input power frequency: 45-66Hz
- Record Length: 4K points per Channel

2. Agilent 34970A Data Acquisition/Switch Unit :

Data Acquisition System was used to automatically record the daylight and interior Lux level automatically throughout the day. Then the data can be retrieved with specialized software program that provides a desktop interface for collecting the dataset.

Figure 7.2: Agilent 34970A Data Acquisition/Switch Unit

Some technical specifications are given below-

- Number of channels : 20 voltage and 2 current analog input
- Scanning speed: 60 ch/s
- Open/close speed: 120/s
- Supply : 300V,1A,50W
- Bandwidth: 10MHz
- Operating temperature: 0-55° C

3. METRAVI 1332 Digital Lux Meter Peak/Data Hold:

Standard METRAVI 1332 Lux Meter was used to calibrate other Luxmeters for DLP light output experiment. Calibration was done by bench photometer technique. It was also used to calibrate the TSL-2561 sensor chip.

Figure 7.3: METRAVI 1332 Digital Luxmeter

Some technical specifications are given below-

- Display: 2000 counts, Large LCD display
- Sensor: Silicon photodiode and sensor
- Measuring Range: 20,200, 2000, 20000, 200000 Lux
- Accuracy: 3%(Calibrated to standard incandescent Lamp,2856K)
- Angle deviation from cosine characteristics : at 30°, 2% ; at 60°, 6% ; at 80°, 25%
- Power Supply : 9V NEDA 1604,IEC 6F22,JIS 006P,1pc

4. **LI-COR LI-250A Light Meter** (Sensor only, display device was not used in our experiment):

LI-250A light meter was used to measure the external daylight Lux level for the study of DLP. The analog voltage output was calibrated and fed to data-logger for continuous measurement.

Figure 7.4: LI-COR LI-250A light meter sensor (with analog voltage output)

The technical specifications of LI-250A sensor are given below-

- Accuracy : ± 0.4% (at 25 °C) and ± 0.6% (upto55 °C)of reading ± 3 counts on the least significant digit displayed (all ranges)
- Linearity: ± 0.05%.
- Sensors: Designed for type "SA" sensors; type "SB" and "SL" sensors with BNC connectors
- Lux Range: 0-199Klx

5. FLUKE 107 ,600V,CAT-III digital multi-meter :

Digital multi-meter was used to measure the variation of Triac output voltage, which was fed to dimmable driver of LED. The variation of light output with change in supply voltage for LED, was thus measured.

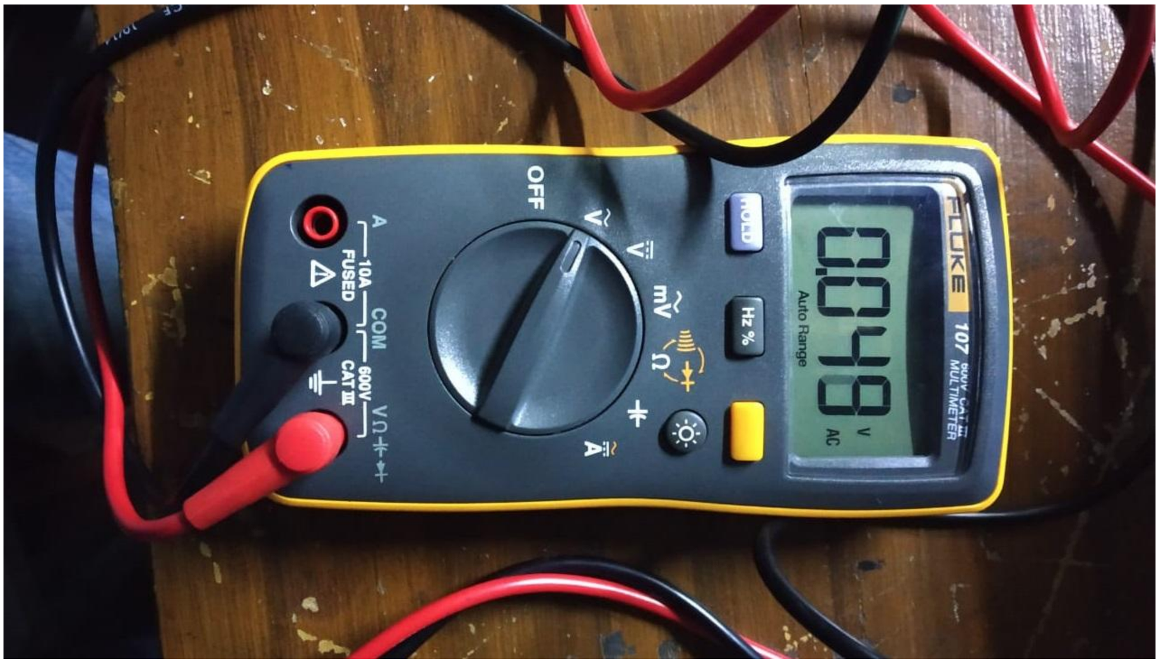

Figure 7.5: FLUKE 107, 600V, CAT-III digital multi-meter

The specification of FLUKE 107, 600V, CAT-III digital multi-meter is highlighted below-

- AC Voltage range: 6 Volt to 600 Volt maximum, with 0.001V to 0.1V resolution
- DC Voltage range: 6 Volt to 600 Volt maximum, with 0.001V to 0.1V resolution
- AC Voltage minimum range: 600mVolt, with 01.mV resolution
- Resistance: 400 Ω to 40M Ω, with 0.1 Ω to 0.01 Ω resolution
- Capacitance: 50nF to 500nF
- Frequency: 50Hz to 100KHz
- Current: 10A maximum, AC or DC

6. **Isolation Transformer:**

The isolation transformer was used to isolate the ground of the oscilloscope from the common ground. If the isolation is not provided, then there is a chance of damage of oscilloscope due to circulation current in the ground wire. The isolation transformer that was used, was a product IS/00K20 by INDUSREE, Kolkata.

The specification of the Isolation Transformer are given below-

- 1 phase, 50 Hz, AN cooling, 500 VA, 230VAC/230VAC (no load).

7. **LUTRON LX-102 Light Meter:**

9 of these light meters were used to study the DLP output in the room interior. These were placed symmetrically at work-plane height of the room, to study the spatial distribution of DLP output. These were calibrated against the standard meter and their analog output was fed into the data acquisition system.

Figure 7.6: LUTRON LX-102 Light Meter

Technical specification of LX-102 light meter are shown-

- Lux Range: 0-50000 lx, 3 ranges(2,000 lx with 1 lx resolution;20,000 lx with 10 lx resolution;50,000 lx with 100 lx resolution)
- Accuracy: ± 5% in all ranges
- Sampling time: 0.4 second
- Analog output: 0.1mV/1 digit, Maximum 200.0 mVolt

- Power supply: DC 9V battery, 0.006P,MN 1604 or equivalent
- Operating temperature: 0 °C to 50 °C

8. AE DIMMERSTAT 8D-1P as variac:

Variac was used to provide output voltage continuously between 0 Volt to 240 Volt AC, from a supply voltage 240 Volt AC. This continuously varying voltage was used to vary the light output of GLS lamp, in the process of calibration of TSL-2561 light sensor.

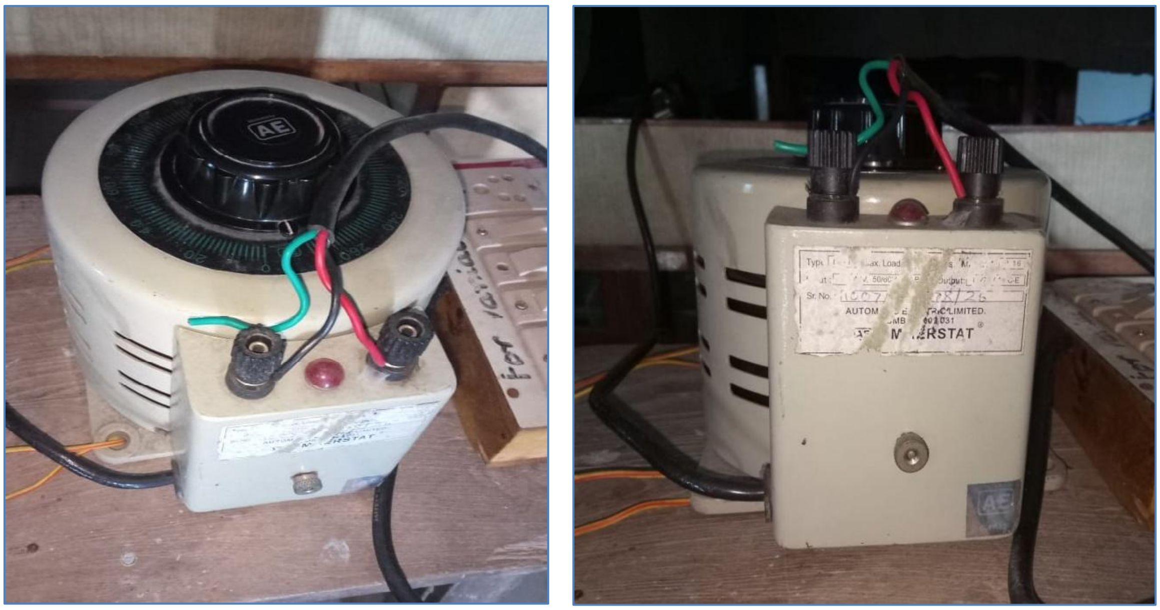

Figure7.7: AE DIMMERSTAT 8D-1P: top view (Left) and side view (Right)

Technical specification of the variac is given below-

- Operating Voltage: 240VAC ,50-60Hz,single phase and 415VAC, 50-60 Hz, three phase
- Insulation Resistance: 5M Ohm at 500V DC
- Dielectric strength: 205kV RMS for 1 minute
- Operating Temperature: 0 °C to 45 °C
- Conforms to: IS 5142

Annexure B: Microcontroller Program

Arduino Program for Integrated System Control (as in experiment 4.5)

```
#include <avr/io.h>
#include <avr/interrupt.h>
#include <Wire.h>
#include <Adafruit_Sensor.h>
#include <Adafruit_TSL2561_U.h>

Adafruit_TSL2561_Unified tsl = Adafruit_TSL2561_Unified (TSL2561_ADDR_FLOAT, 12345);
                                  //set-up address for I2C comm's

const double lookUpTable[125][5] =
{                                 //DIALUX generated dimming matrix
20, 20, 20, 99, 0.842,
20, 20, 40, 130, 0.785,
20, 20, 60, 162, 0.748,
.................................  //Total 125 entries (not shown here)
100,100,60,429,0.875,
100,100,80,461,0.856,
100, 100, 100, 493, 0.842
  };

#define DETECT 2                  //zero cross detect
#define GATE 9                     //Triac gate
const int rows =125 ;              //declaration of global variables
const int columns = 5;
volatile int PULSE=20 ;
int i=0;
int d1=0;
int d2=0;
int d3= 0;

void setup()
{
  pinMode(DETECT, INPUT);              //set-up pins for zero cross detect
  digitalWrite(DETECT, HIGH);          //enable pull-up resistor
  pinMode(GATE, OUTPUT);               //Triac gate control
  Serial.begin(9600);

  OCR1A = 100;                         //initialize the comparator to set up Timer1
```

```
 TIMSK1 = 0x03;                          //enable comparator A and overflow interrupts
 TCCR1A = 0x00;                          //timer control registers set for
 TCCR1B = 0x00;                          //normal operation, timer disabled
 attachInterrupt(0,zeroCrossingInterrupt, RISING);        //attach interrupt to pin 2
}
void zeroCrossingInterrupt()
{                                        //zero cross detected, ISR called
 TCCR1B=0x04;                            //start timer with divide by 256 input
 TCNT1 = 0;                              //reset timer - count from zero
}
ISR(TIMER1_COMPA_vect)
{                                        //comparator match
 digitalWrite(GATE,HIGH);                //set TRIAC gate to high
 TCNT1 = 65536-PULSE;                    //trigger pulse width
}
ISR(TIMER1_OVF_vect)
{                                        //timer1 overflow
 digitalWrite(GATE,LOW);                 //turn off Triac gate
 TCCR1B = 0x00;                          //disable timer stopped unintended triggers
}

void loop()
{
 sensors_event_t event;
 tsl.getEvent(&event);                   //sensors data getter function
 for(int i=0;i<16;i++)
{
 float targetIlluminance = 500;          //target illuminance 500lx
 float externalIlluminance = event.light;       //picks external lx from TSL-2561
if(externalIlluminance>=500)
{
 externalIlluminance = 500;              //LED gets switched OFF
}
 float artificialIlluminance = targetIlluminance - extContribution;   // local variables declared
 float AIlowerLimit = artificialIlluminance-10;
 float AIUpperLimit = artificialIlluminance+10;       //setting upper and lower limit for Look-up-table
 float lastSavedUniformity=0;
 float newUniformity = 0;
 float predictedArtificialIlluminance = 0;
for ( int i = 0; i < rows; ++i )
{                                           //checks each entry of look-up-table for illuminance match
int generatedartificialIlluminance=lookUpTable[ i ][ 3 ];
if(generatedartificialIlluminance>AIlowerLimit && generatedartificialIlluminance<AIUpperLimit)
{                                            //match found
```

```
  newUniformity= lookUpTable[ i ][ 4 ] ;
  if(newUniformity>lastSavedUniformity)      //Uniformity maximization
{
  d1 = lookUpTable[ i ][ 0 ];                 //Stores d1
  d2 = lookUpTable[ i ][ 1 ];                 //Stores d2
  d3 = lookUpTable[ i ][ 2 ];                 //Stores d3
  predictedArtificialIlluminance = lookUpTable[ i ][ 3 ];          //Stores predicted lx
  lastSavedUniformity = newUniformity;                             //Stores Uniformity
}
}
}
  float predictedArtLux = d1*5.05;
  float timerCountFloat = 519.13- 0.0000084196*(predictedArtLux*predictedArtLux*
  predictedArtLux)+0.0061*(predictedArtLux*predictedArtLux)-     1.8896*predictedArtLux ;

                                              //Wait Count calculated for predicted lx

  int timerCount = (int)timerCountFloat;
  OCR1A = timerCount;                         //feeds Wait Count to ISR
  PULSE = 625-timerCount;
  delay(10000);
}
}
```