UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND INFORMATION ENGINEERING

Intelligent Multi-Coloured Lighting System Design with Fuzzy Logic Controller

By

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F56/69356/2011

A thesis submitted in partial fulfillment for the Degree of MSc. Electrical and Electronics Engineering in the Department of Electrical and Information Engineering in the University of Nairobi

<u>Previous Degrees Attained:</u>

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JULY 2015

Declaration of Originality

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Dedication

This research work is dedicated to my family: My late wife, Eunice Mwikali, for her patience and special support. My son, Emmanuel Muthoka, for encouraging and renting me his only laptop computer for this research work. My daughter, Rael Munyiva, for her prayers and spiritual strength.

Acknowledgements

I would like to take this opportunity to thank my supervisor, Prof. M. Mbuthia, for his valuable guidance and support throughout my MSc. course and this research work. May Almighty God bless you in plenty as you endeavor to make the university research work interesting and of help in producing knowledge. I also want to acknowledge Dr. C. Wekesa and the other lecturers, at the Electrical and Information Engineering department, for their personal support and positive critic. It could have been almost impossible without your support. You were God sent. I thank God for you.

I take this early opportunity to thank the top management of my company, KenGen, for allowing me to think freely on engineering academics and by extension sponsoring my MSc. studies. I would be pleased to pass my special gratitude to the Operations Director, Eng. R. Nderitu, and the Human Resources & Administration Director, Mrs. B. Soi, for their personal encouragement and support throughout my studies. I want to give special thanks to my immediate senior, Eng. S. Kariuki, and the other managers at KenGen for their understanding and support during the studies and preparation of this thesis. I would also want to thank my office colleague, Eng. H. Ng’iela, for his positive critic and many discussions on how to compile a good thesis.

I would also like to thank my postgraduate colleagues and all staff in the Department of Electrical and Information Engineering, University of Nairobi, for their support and encouragement.

I would like to thank my family, my immediate local Kalambya/Thinu community, and friends for their encouragement and support throughout my studies and preparation of this thesis. Finally, I take this opportunity to thank my Lord God for guarding and guiding me throughout the studies.

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List of Abbreviations and Nomenclature

List of Abbreviations

AI	- Artificial Intelligence
ANFIS	- Adaptive Neuro-Fuzzy Inference System
B-LED	- Blue LED
b_r	- colour blue part ratio
CFL	- Compact Fluorescence Lamp
CIE	- International Commission on Illumination
CRI (Ra)	- Colour Rendering Index
cd	- Candela
C_p	- Colour product signal
C_s	- Decoded/selected colour signal
DALI	- Digital Addressable Lighting Interface
ECG	- Electronic Control Gear
EN	- European Standard
FL	- Fuzzy Logic
FIS	- Fuzzy Inference System
g_r	- colour green part ratio
G-LED	- Green LED
IEEE	- Institute of Electrical and Electronics Engineers
LED	- Light Emitting Diode
lm	- Lumen
lx	- lux
l_{od}	- Outdoor light level signal
l_{odr}	- Outdoor light illuminating the room
l_k	- Indoor light level signal
MF	- Membership Function
M_d	- Movement detection signal
p_r	- Window shade position reference signal
PWM	- Pulse Width Modulation
R-LED	- Red LED
RGB LED	- combined Red, Green, and Blue colour LEDs (Multi-colour LED)
r_r	- colour red part ratio
R_o	- Room occupancy signal
Sc	- Simulink Scope block
Δl_k	- Indoor light level rate of change

List of Nomenclature

Colour product signal – is the product of Red, Green, and Blue colour ratios in light colour mixing.

Decoded/selected colour signal – the summation of Red, Green, and Blue colour ratios in light colour mixing.

Fuzzy Logic – Logic of words and not numbers. A logic set of linguistic variables.

Fuzzy Logic Controller – Digital controller based on fuzzy logic.

Fuzzy inference – the process of formulating the mapping from a given input to an output using fuzzy logic.

Illuminance - is the quantity of light falling on a unit area of a surface in lux (lx).

Intelligent system – a system of electrical, electronic and mechanical devises, that is in a position to sense, calculate logic and act reasonably to produce a required result.

Indoor light – illuminance in an enclosed space or room

Lumen - a measure of amount of light given by a point source (lm).

Luminance level – quantity of light emitted from a light source (e.g. LEDs) in cd/m^2.

Luminous efficacy - is the ratio of luminous flux to electrical power of the light source (lm/w).

Light Intensity - quantity or brightness of light on a surface.

Lighting design – the art and craft of creating the visual environment by means of illuminating it.

Membership Function - This is a mathematical function represented in a curve/graphical plot where the x-axis is a range of crisp values but the y-axis is fuzzy values which always range from 0 to 1.

Multi-coloured lighting system – a lighting system that uses RGB LEDs as one of its source of coloured light.

Window Shade position - Opening level of a light blinding shade for a room window.

Abstract

This thesis is about design of an intelligent energy efficient lighting system based on fuzzy logic controller that uses multi-colour LEDs to produce light of the required luminance level and appropriate colour in a typical room space. The lighting system incorporates automatic controlling of a room's window shade opening, conveniently harvesting daylight. Appropriate room occupancy sensors were set to dim off the LEDs if there are no people in the room. A movement sensor was also considered for dimming the LEDs if the persons in the room are asleep. A colour sensor or decoder was included in the control system to dim off the LEDs if the colour signal is not initiated. The colour decoder signal determine the LEDs' output light colour, and close the window shades if the required room's light colour is not white. Two Fuzzy Logic controllers were used in the system; the first one to control opening of the room's window shades, and the other to control the LEDs' output luminance level.

The study was limited to simulation of the design in a MATLAB software environment. However, a proposal of the appropriate hardware that could be used to actualize the lighting system was also researched and a labeled block diagram for the same provided.

The appropriate devices were identified, configured and assembled into a complete operating simulate system using a MATLAB-Simulink applications software. The designed system was simulated in the computer MATLAB environment, and the results were observed and monitored using the associated Simulink scopes.

The LEDs were observed (via current pulse width) to dim accordingly in response to level of illumination in the room; the higher the outdoor light into room, the smaller the luminance from the LEDs. If outdoor light is very low, the window shade was observed to close. Also observed was the window shade closing when the LEDs output light colour is not white. The simulated model was able to calculate accurately the respective primary colour-part ratios, where the values were used in driving the RGB LEDs for production the required room lighting colour. The designed multi-coloured LED lighting system model is intelligent in saving lighting electric energy, and providing room illumination levels and lighting colour requirements.

CHAPTER 1- **INTRODUCTION**

1.1 Background of the study

Nowadays lighting is seen also as a way of creating a pleasant atmosphere in the interior as a whole and as a means of providing comfortable conditions in which to live and work. It is not there just to improve visual perception, but also to determine the emotional atmosphere: cool or warm, businesslike or pleasant, happy or solemn [11].

Since the discovery and use of incandescent electric lamps by end of 19th century, lighting systems have undergone many major developments. Research for more efficient lighting system is an on-going exercise driven by the need to save energy, the international requirements to reduce greenhouse gases, and high cost of electricity from renewable energy sources. Lighting can account for up to 20% of a household's yearly electricity usage, and up to 40% a year in commercial buildings [9][11].

Energy lighting efficient research could be classified in three focuses: lamp technologies, lighting design, and lighting control methods [1]. The three focuses could be optimized by integrating them with an appropriate artificial intelligence (AI) system.

The current generations of light emitting diodes (LEDs) are more efficient, some having efficacies of more than 100 lm/w [16][19][20][25][33]. The use of control technology in electric light dimming, daylight harvesting, and movement detection can greatly improve lighting energy efficiency [8][11][19][20]. The LED characterized by mercury-free, high efficiency, and long life cycle is expected to be the new generation of light source [1][25][33].

The new generation of multi-colour RGB (Red, Green, Blue) LEDs offer not merely another means to form white light but a new means to form light of different colours. As more effort is devoted to investigating this method, multi-colour LEDs should have profound influence on the fundamental method that we use to produce and control light colour [15][16][25][33].

To achieve a desired quality of light for a space, various lighting control systems have been explored and described, including use of Digital Addressable Light Interface (DALI), Programmable Logic Controllers (PLC), digital signal controllers (DSC), and Fuzzy Logic Controllers [1][2][13][14][18][21][23][24][28][29][31][32].

Fuzzy logic, a branch of artificial intelligent (AI) systems, is a form of algebra employing a range of values from "false" (0) to "true" (1) that is used in making decisions with imprecise data. Fuzzy logic is a very powerful tool for dealing quickly and efficiently with imprecision and non-linearity issues, like light intensity level in a room, requiring decision making [6][7][24][26].

Energy saving has been identified as the major concern in designing any intelligent energy efficient lighting system [1][9][30].

1.2 Statement of the Problem

The lighting industry is going through a radical transformation driven by rapid progress in multi-colour LED lighting, information technology, and the need for sustainable and energy-efficient solutions. Demands on lighting systems have changed considerably in recent years. While just switching individual lights on and off used to be sufficient, the new focus is on dynamic lighting [5][19]20].

There is need to optimize the applications of new generation of multi-colour LEDs and the intelligent systems, which in combination with advanced digital addressable sensors and controls, will fuel new lighting applications. Application of Artificial Intelligent (AI) software programs in control of multi-coloured light sources is bound to become a way of life in the near future and lead to new lighting solutions, which are not possible with conventional lighting technology.

It is necessary to optimize utilization of natural light in both homes and work places as a strategy to save lighting related energy costs, and at the same time improve comfort of living and working in such places. To do this we need to monitor and adjust the amount of light intensity in the user places. Manually, on/off switching and discrete level dimmers can be used to control the amount of light provided in a space, however, there is not much timing accuracy using this technique – and people also forget. It is therefore necessary to automate lighting intensity control in a space.

This study was seeking for a way to automate light intensity and colour control in a space using fuzzy logic controllers.

1.3 Objectives of the study

1.3.1 The Main Objective

The main objective of this study was to design an intelligent lighting system based on fuzzy logic controller that uses multi-colour LEDs to produce light of the required luminance level and appropriate colour in a room space considering energy efficiency requirements.

1.3.2 The Specific Objectives

The specific objectives of the research study were:

1. To design hardware and control algorithms for an outdoor lighting level sensor to automatically control a room's window shade position;
2. To design hardware and control algorithms for an indoor lighting level sensor to intelligently adjust the LEDs' output light to the required room's illuminance level;
3. To design hardware and control algorithms for an occupant detector that counts the number of persons in a room and dim off the LEDs light if the room is not occupied;
4. To design hardware and control algorithms for a movement detector that dims off the LEDs light if a movement in the room is not detected;
5. To design a colour decoder/sensor hardware and control algorithms for determining the multi-colour LEDs' output light colour and open the window shade if output light colour is white;
6. To integrate all the sensors' subsystems into energy efficient automated intelligent multi-coloured lighting system.

1.4 Research Questions

The following specific questions were used as guide for the research study:

1. How can the output of an outdoor lighting level sensor be configured and processed to automatically control a room's window shade position?
2. How can the output of an indoor lighting level sensor be configured and processed to intelligently control LEDs' luminance and maintain the required room's illumination levels?
3. How can the output of an occupant detector that counts the number persons in a room be configured and processed to dim off the LEDs lights if the room is not occupied?
4. How can the output of a movement detector be configured and processed to dim off the LEDs if a movement in the room is not detected?
5. How can the output of a colour decoder/sensor be processed to accurately determine the multi-colour LEDs' output light colour and at the same time close the room's window shades if the output light is not white?
6. Can the integrated system of addressable sensors, window shade, fuzzy logic controllers, and multi-colour LEDs provide a typical room with light of appropriate colour at required intensity levels and still be efficient in electrical energy usage?

1.5 Motivation and Benefits of the research study

The author believes human beings live to enjoy life to fullest levels possible. Light is one of the major sources of enjoyment in life. It is through light that we perceive exciting beauty in our surroundings.

Research study on how to extract greater excitements from light, and especially on how to create dynamic intelligent automatic coloured scenes using the new generation of multi-coloured LEDs is on high demand.

Energy efficiency and sustainability are major concerns in society today. Fuzzy logic controller, whose operation is based on expert's knowledge and human reasoning, could be the best option for modeling an intelligent and energy efficient lighting system, which do not require fine accuracy in illumination levels.

The knowledge gained from this research study would be beneficial to the universities and lighting industries. This thesis would form a basis for further studies on artificial intelligent systems energy saving and lighting colour control. This thesis would be used in improving energy and comfort performance of modern smart buildings.

1.6 Scope and Limitations of the Study

This thesis is about use of Fuzzy Logic concept in automating opening of window shades and energy efficiency control of RGB LEDs' output light intensity in a typical room space. The study was limited to simulation of the lighting system design using Simulink blocks on a MATLAB environment.

However, a physical implementation scheme for the lighting system, using appropriate microprocessors and addressable digital sensors, was researched and proposed for future works.

CHAPTER 2- **LITERATURE REVIEW**

2.1 Introduction

In this chapter, literature on issues concerning light has been reviewed and explained in terms of what light is, quality of light, measurements and definitions of light, sources of light, concepts of designing lighting systems, LEDs, and lighting control systems. Also reviewed is the concept of Fuzzy Logic, Fuzzy logic controllers and lighting systems based on logic controllers. A concept design for the Intelligent Multi-coloured Lighting System with Fuzzy logic controllers is also described.

2.2 Light and Sight aspects

2.2.1 What is light?

Light is a **form of energy** manifesting itself as electromagnetic radiation. The human eye responds to wavelengths between 380nM and 780nM of the spectrum. The eye interprets the different wavelengths within this range as **colours** – moving from violet, indigo, blue, green, yellow, orange, and red as wavelength increases [9][35]. Sight, therefore, is one of the most vital sense mankind possesses and understanding of how the eye works and how the brain responds to the visual stimuli they receive is crucial to understanding the way light impacts on our lives [9].

We all live in a world where at some point, colour will be a part that affect us in our everyday lives [35]. Colour in everyday life is very diverse, from knowing that a fruit is ripe to eat, to understanding how colour can affect our moods; blue can be calming, red can make you tense [35].

The retina in our eyes have three types of colour receptors in the form of cones. We can detect only three of these visible colours – red, blue and green. These colours are called additive primaries. It is these three colours that are mixed in our brain to create all of the other colours we see [35].

These are called the primary colours and additive mixing of these colours will produce all other light colours, including white. Figure 2.1 illustrates the additive colour mixing [9][35].

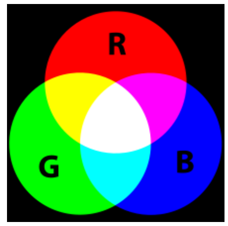


Figure 2.1: Additive colour mixing illustration

Where: red + green = yellow, red + blue = magenta (purplish red), green + blue = cyan (sky blue), and red + green + blue =white

2.2.2 Quality of Light

Good quality lighting is a crucial factor affecting our ability to perform tasks at work and at home. It embodies a combination of several criteria including lighting level, luminance contrast, glare and spatial distribution of the light, colour and colour rendering [9].

Although white light is a mixture of colours, not all whites are the same since they depend on their constituent colours. So a white with a higher proportion of red will appear warmer and a white with a higher proportion of blue will appear cooler [9][11].

2.2.3 Measurements and Definitions of some lighting terms

Photometric measurement is based on photo-detectors, devices (of several types) that produce an electric signal when exposed to light [1][9].

Photometry is the science of the measurement of light, in terms of its perceived brightness to the human eye. In photometry, the radiant power at each wavelength is weighted by a luminosity function that models human brightness sensitivity; weighted according to how sensitive the human eye is to it [9].

The **lumen** is defined as amount of light given into one steradian by a point source of one candela strength; while the candela, a base SI unit, is defined as the luminous intensity of a source of monochromatic radiation, of frequency 540 terahertz (555nm – wavelength, in the green, to which the human eye is most sensitive) and a radiant intensity of 1/683 watts per steradian. Therefore 1/683 watt of 555 nanometre green light provides one lumen. The definition tells us that 1 watt of pure green 555nm light is "worth" 683 lumens.

Luminous flux expresses the total quantity of light radiated per 1 second by a light source. The unit of luminous flux is the **lumen (lm)**.

Luminous intensity is defined as the flux of light emitted in a certain direction. The unit of luminous intensity is the **candela (cd)**.

Illuminance is the quantity of light falling on a unit area of a surface. The unit of illuminance is lumen/m^2, or **lux (lx)**.

Luminance describes the light emitted from a unit area in a specific direction. The unit of luminance is expressed in **cd/m^2** (apparent surface).

Luminous efficacy is a measure of how well a light source produces visible light. It is the ratio of luminous flux to power (lm/w). The luminous efficacy of a source is a measure of the efficiency with which the source provides visible light from electricity.

Colour Rendering Index (CRI also denoted as **Ra)** describes the effectiveness of white light to render all the visible colours on illuminating a surface. The scale of the Ra ranges from 50-100.

2.3 Sources of Light

There are three main sources of light; Sun - the source of daylight, Chemicals - the source of fire flame, and Electricity - the source of electric light.

Sun is the source of the natural daylight. The utilization of the daylight with appropriate shading device control in buildings is useful to complement or replace the other lighting forms, which results in significantly lower energy consumption for lighting, while maintaining the occupants' visual comfort [18].

Electricity is the most modern form of energy which can conveniently be converted to visible light energy. The quantity and quality of the light produced can easily be controlled based on the type of light source device and the average power to the light producing device.

Various types of electric light producing devices (lamps) have been developed. Incandescent lamp is the second oldest form of electric lighting. When incandescent lamps first appeared by the end of the 19th century, their efficacy was just 3 lm/W, which has improved to around 14 lm/W today [9]. The halogen incandescent lamp has luminous efficacy of about 5-27 lm/w at colour rendering index of 100 Ra.

Low-pressure sodium lamp has luminous efficacy of about 100-203 lm/w with colour rendering index less than 30Ra. High-pressure sodium lamp has luminous efficacy of about 50-130 lm/w at colour rendering index of 10-80 Ra [9].

The compact fluorescent lamp (CFL) is basically a low-pressure mercury gas discharge lamp with luminous efficacy of about 60-105 lm/w at colour rendering index of 60-95 Ra. High-pressure mercury lamp has luminous efficacy of about 35-60 lm/w at colour rendering index of 40-60 Ra. Metal halide lamps have luminous efficacy of about 75-140 lm/w at colour rendering index of 65-95 Ra. A more recent development is the ceramic metal halide lamp, which has luminous efficacy of about 68-90 lm/w at colour rendering index of 80-95 Ra.

The most recent evolution in lighting is solid-state lighting based on light emitting diode (LED) technology. LED has luminous efficacy of about 50-130 lm/w at colour rendering index of 10-90 Ra [9] [11].

2.4 The Concept of Designing a Lighting System

A lighting system is a string of modules that are connected systematically to produce light of the desired quantity and quality at the required space and time. Lighting design, on the other hand, is the art and craft of creating the visual environment by means of illuminating it.

Light gives us beauty as well as vision, and the quality is often far more important to us than the quantity. Good lighting is both a science and an art, combining knowledge of physics, engineering, design, physiology and psychology. Nowadays lighting is seen also as a way of creating a pleasant atmosphere in the interior as a whole and as a means of providing comfortable conditions in which to live and work [11].

Lighting system is not there just to improve visual perception, but also to determine the emotional atmosphere: cool or warm, businesslike or pleasant, happy or solemn. This is the lighting designer’s task, which is achieved by creating comfortable and stimulating lighting systems [9][11].

The EN 12464-1 standard specifies requirements for lighting systems for almost all indoor work places and their associated areas in terms of quantity and quality of illumination [9][34]. Around the world Legislation sets targets for the reduction of greenhouse gases, reduction or elimination in the use of hazardous substances such as mercury and lead and mandatory recycling of used lamps [9].

Nowadays a great portion of our source of energy is from fossil fuel that will be exhausted soon. The cost of electricity is going to increase due to the need of investments in renewable energy supply and shortage of crude oil [9][21].

Today, energy efficiency is an essential element of every home and business. In fact, lighting can account for up to 20% of a household’s yearly electricity usage, and up to 40% a year in commercial buildings. The use of control technology, dimming, daylight equalization, movement detection to schedule power management through control and dimming of lights can greatly improve efficiency going forwards. Most dimmable CFLs will dim down to 10% to 30% measured light output. Early versions of dimmable LEDs on the market have the ability to dim lower than CFLs and can reach levels as low as 5% to 15% measured light [20].

Energy lighting efficient research could be classified in three focuses: lamp technologies, lighting design, and lighting control method [1].

2.5 Light Emitting Diodes (LEDs)

A light-emitting diode (LED) is a semiconductor light source. LEDs were initially used as indicator lamps in many devices and are increasingly used for other lighting. Appearing as practical electronic components in 1962, early LEDs emitted low-intensity red light, but modern versions are available across the visible spectrum, ultraviolet, and infrared wavelengths, with very high brightness.

When a light-emitting semiconductor diode is forward-biased (switched on), electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. Colour of the light produced (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor. A LED is often small in area (less than 1 mm^2), and integrated optical components may be used to shape its radiation pattern.

At the heart of every white LED is a semiconductor chip made from nitride-based materials. The chip is traditionally positioned on top of the cathode lead. Applying several volts across this device makes the chip emit blue light. Passing the blue light through a yellow phosphor yields white light. Modern, high-power LEDs are variants of this architecture, featuring more complex packages for superior thermal management. Figure 2.2 is a visual illustration of LED lighting principles [22].

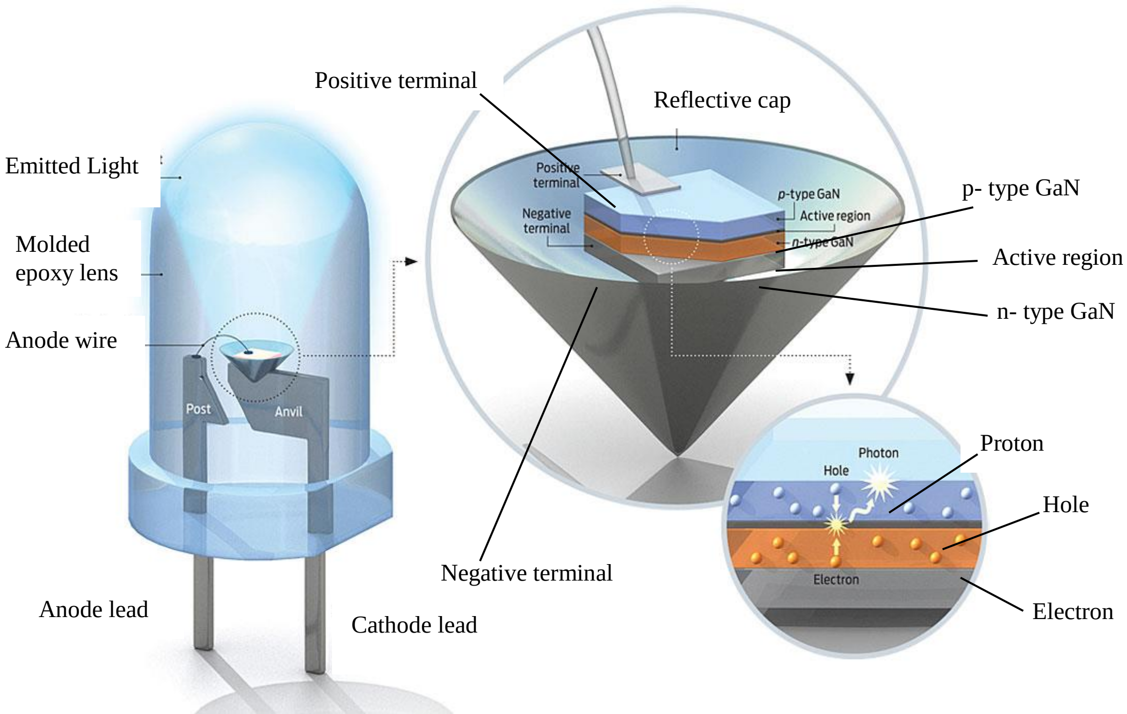


Figure 2.2: Parts of an LED with detailed light source architecture. Illustration by Bryan Christie [22]

The efficiency of conventional InGaN based LEDs decreases as one increases current above a given level. This phenomenon of decrease in efficiency is called droop. Solving this mystery will enable the design of droop-busting LED architectures that will make brighter cheaper solid-state lighting [22].

By its very nature, LEDs can only generate monochromatic colours. Giving LEDs the blues in 1994, was the key to replacing the incandescent bulb. The first high-brightness blue LED was demonstrated by Shuji Nakamura of Nichia Corporation in 1994 and was based on InGaN (Indium Gallium Nitrade). In September 2003, a new type of blue LED was demonstrated by the company Cree Inc. to provide 24 mW at 20 milliamperes (mA). This produced a commercially packaged white light giving 65 lm/W at 20 mA, becoming the brightest white LED commercially available at the time, and more than four times as efficient as standard incandescent lamps [22][25][33].

There are two primary ways of producing White Light-Emitting Diodes. One is to use individual LEDs that emit the three primary colors- red, green, and blue (RGB) and then mix all the colors to form white light. The other way is to use a phosphor material to convert monochromatic light from a blue or UV LED to broad-spectrum white light, much in the same way a fluorescent light bulb works.

So in order to create white light, two or more colours need to be combined. The blue one can be added to existing red and green LEDs to produce the impression of white light. Figure 2.3 shows combined spectral curves for blue, yellow-green, and high-brightness red at respective radiation wavelengths.

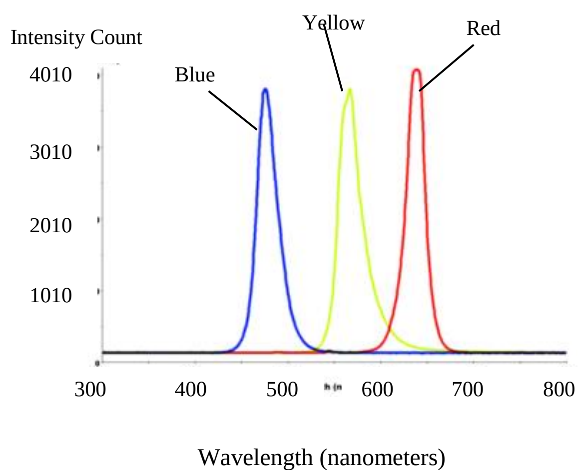


Figure 2.3: Combined spectral curves for blue, yellow-green, and high-brightness red solid-state semiconductor LEDs [25].

Figure 2.4 is a photograph of a single LED with four leads for three inbuilt RGB LEDs. Figure 2.5 is a cross-section of white LEDs lamp showing part of the electronic driver board.

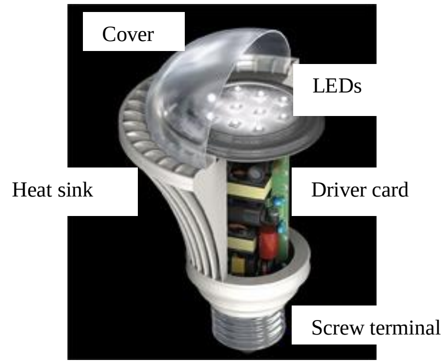


Figure 2.4: Photograph of a four leads RGB LED **Figure 2.5:** cross-section of LED lamp[25]

One solution for white LED light is by mixing red, green and blue (RGB) semiconductor chips into one single LED, or, by placing separate red, green and blue LEDs very close together, and optically mixing the emitted radiation. Hence the method is called multi-colour white LEDs (sometimes referred to as RGB LEDs). This method is particularly interesting in many uses because of the flexibility of mixing different colours, and, in principle, this mechanism also has higher quantum efficiency in producing white light.

As more effort is devoted to investigating the effective methods of mixing light colours, multi-colour LEDs should have profound influence on the fundamental method that we use to produce and control light colour [20][25][33].

In 2012, Cree announced a white LED giving 254 lumens per watt. In December 2012 Cree issued another press release announcing commercial availability of 200 lumens per watt LED at room temperature [20].

With the development of high-efficiency and high-power LEDs, it has become possible to use LEDs in lighting and illumination [22][33].

2.6 Lighting Control Systems

A lighting control system consists of a device that controls electric lighting and devices, alone or as part of a daylight harvesting system, for a public, commercial, or residential building or property, or the theater [8]. Lighting control systems, with an embedded processor or industrial computer device, usually include one or more portable or mounted keypad or touch-screen console interfaces, and can include mobile phone operation [8][36][37]. These control interfaces allow users the ability to remotely toggle (on-off) power to individual or groups of lights, operate dimmers, and pre-program space lighting levels.

Intelligent lighting can be as simple as automating a single light, so that it can be controlled by a remote control device or timer. Intelligent lighting also refers to stage lighting that has automated or mechanical abilities beyond those of traditional, stationary illumination. Intelligent lighting is also known as automated lighting, moving lights or moving heads [8][27]. Demands on lighting systems have changed considerably in recent years. While just switching individual lights on and off used to be sufficient, the new focus is on dynamic lighting [5][19]20]. The storage and retrieval of entire lighting scenes is also in demand in this context. In order to create lighting scenes, lights have to be assigned to particular groups, but as a rule, the end-user also wants the option of controlling the lights individually [4][5][10].

Digital Addressable Lighting Interface (DALI) is a draft standard for a digital interface for controlling (dimmable) electronic control gear (ECG). DALI is a joint development by a majority of the lighting industry. The aim in developing DALI was to create a uniform standard in the lighting industry and fill the gap between previous 1-10V control lighting interface technology and more complex bus systems [4][5][10].

2.7 Concept of Fuzzy Logic

2.7.1 Fuzzy Logic

Fuzzy logic is a branch of Artificial Intelligence (AI) developed by Lotfi Zadeh in 1965 [7][12][24]. Fuzzy logic is a superset of Boolean logic dealing with the concept of partial truth - truth values between "completely true" and "completely false" [6][7][12]. In classic Boolean logic, a value is either 1 (**one** – completely true) or 0 (**zero** – completely false) but cannot be there between as it is with Fuzzy logic.

The basic concept underlying fuzzy logic is that of a linguistic variable, that is, a variable whose values are words, such as large, small, very bright, etc, rather than numbers. Fuzzy logic is all about the relative importance of precision- “how important is it to be exactly right when a rough answer will do?” [12][24].

Fuzzy logic uses fuzzy sets to relate classes of objects with unclearly defined boundaries in which membership is a matter of degree. Fuzzy logic is a form of algebra employing a range of values from "true" to "false" that is used in making decisions with imprecise data. The outcome of an operation is assigned a value between 0 and 1 corresponding to its degree of truth [6][7] [24][26].

2.7.2 Fuzzy sets

The idea of grade of membership, which is the concept that became the backbone of fuzzy set theory, occurred to Lotfi A. Zadeh in 1964, leading to the publication of his seminal paper on fuzzy sets in 1965, which marked the birth of fuzzy logic technology [6][7][24].

Fuzzy sets is a class of objects with a continuum of grades of membership. Such a set is characterised by a membership (characteristic) function which assigns to each object a grade of membership ranging from zero to one [6]. Fuzzy sets allow partial membership which means that an element may partially belong to more than one set. The grade of membership ranges from 0 (no membership) to 1 (full membership), written as in equation (2-1).

$$\mu_A : U \rightarrow [0,1] \tag{2-1}$$

which means that the fuzzy set A belongs to the universal set U (called the universe of discourse) defined in a specific problem.

Just as a Boolean predicate asserts that its argument definitely belongs to some subset of all objects, a fuzzy predicate gives the degree of truth with which its argument belongs to a fuzzy subset [6][12][24][26].

2.7.3 Membership Function

A membership function is a function from a universal set U to the interval [0,1]. A membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as "Universe of discourse" [12][24]. Figure 2.6 shows representation of the membership function - input U is mapped to the corresponding degree of membership μ in the range of 0 to 1.

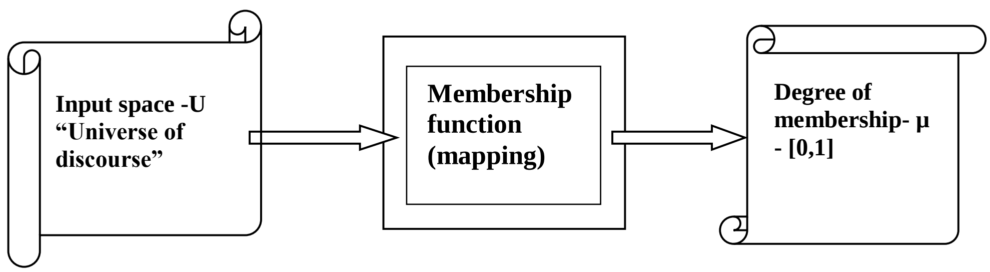


Figure 2.6: Illustration of membership function

The curve known as a "membership function" is often given the designation of μ. The value μ is the degree of membership, which is along the y-axis of the graph. The universe of discourse U is along the x-axis of the membership function graph.

Consider, for example, the set of membership function for a set of tall people. If the set is given the crisp boundary of a classical set such that, if more than 6ft is tall, then less than 6ft is short. This crisp set is illustrated in figure 2.7.

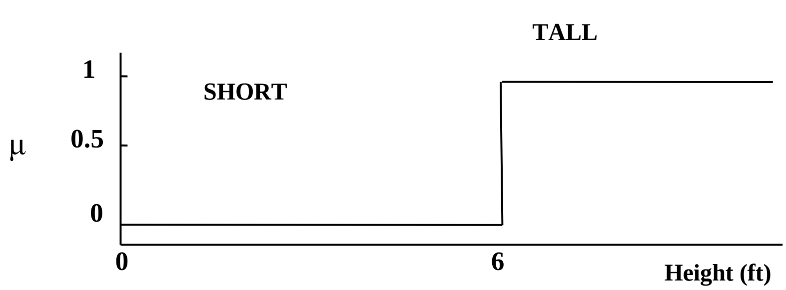


Figure 2.7: Membership function -Set of tall people (**Crisp Set**)

But for more realistic, a smooth curve from SHORT to TALL is a fuzzy set such that a person may be both tall and short to some degree. This is illustrated in figure 2.8.

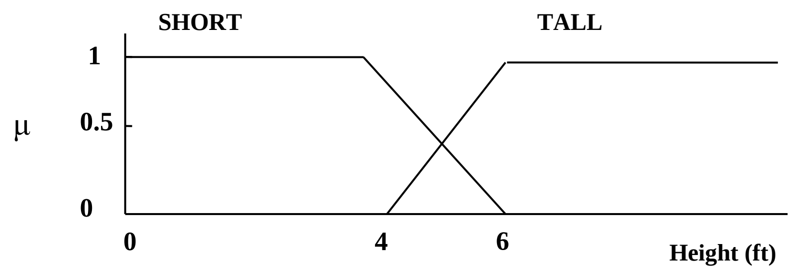


Figure 2.8: Membership function - Set of tall people (**Fuzzy Set**)

2.7.4 Fuzzy Logical Operations

Fuzzy logical reasoning is the fact that it is a superset of standard Boolean Logic. The set operations intersection and union correspond to logic operations, conjunction (AND) and disjunction (OR), respectively. In the fuzzy logic, the statement A ***AND*** B, where A and B are limited to the range (0,1), is resolved by using the function **min**(A, B). Also the operation A ***OR*** B becomes equivalent to **max**(A, B). The operation ***NOT*** A becomes equivalent to the operation **1-A** [6][12][24].

The set operations of intersection (AND), union (OR), and complementation (NOT), are defined in terms of characteristic (membership) functions in the following fuzzy logic equations (2-2), (2-3), and (2-4) respectively:

Intersection: $$\mu_{A \cap B}(x) = \mathbf{min}(\mu_A(x), \mu_B(x)) \quad (2\text{-}2)$$

Union: $$\mu_{A \cup B}(x) = \mathbf{max}(\mu_A(x), \mu_B(x)) \quad (2\text{-}3)$$

Complement: $$\mu_{not\ A}(x) = \mathbf{1}\text{-}\mu_A(x) \quad (2\text{-}4)$$

2.8 Fuzzy Logic Controllers

A fuzzy control system is a control system based on fuzzy logic—a mathematical system that analyzes **analog** input values in terms of logical variables that take on continuous values between 0 and 1. This is in contrast to classical or **digital** logic, which operates on discrete values of either 1 or 0 (true or false, respectively) [26]. Fuzzy logic is used, for example, in artificial intelligence (AI) systems. It is a very powerful tool for dealing quickly and efficiently with imprecision and non-linearity issues requiring decision making.

Fuzzy system is better placed in solving day-to-day problems due to its ability to be built on top of the experience of experts and can be blended with conventional control technologies [12][24]. Traditionally, fuzzy logic has been viewed in the Artificial Intelligence (AI) community as an approach for managing uncertainty. In the 1990's, however, fuzzy logic has emerged as a paradigm for approximating a functional mapping [12][24][26].

Fuzzy logic control relies on basic physical properties of the system, and it is potentially able to extend control capability even to those operating conditions where linear control techniques fail.

A basic application might characterize sub ranges of a **continuous variable** [26]. For instance, a temperature measurement for **anti-lock brakes** might have several separate membership functions, as shown in figure 2.9, defining particular temperature ranges needed to control the brakes properly. Each function maps the same temperature value to a truth value in the 0 to 1 range. These truth values can then be used to determine how the brakes should be controlled.

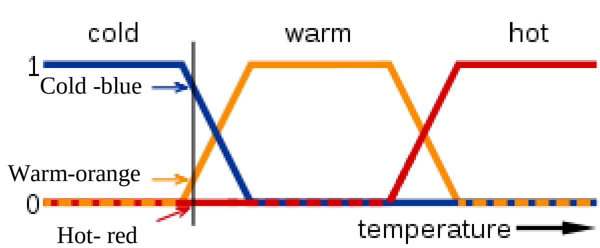


Figure 2.9: Fuzzy logic temperature membership function [26]

In this image, figure 2.9, the expressions **cold**, **warm**, and **hot** are represented by functions mapping a temperature scale. A point on that scale has three "truth values"—one for each of the three functions. The vertical line in the image represents a particular temperature that the three arrows (truth values) gauge. Since the **red** arrow points to zero, this temperature may be interpreted as **"not hot"**. The **orange** arrow (pointing at 0.2) may describe it as **"slightly warm"** and the **blue** arrow (pointing at 0.8) **"fairly cold"** [26].

A fuzzy controller is based on a collection of conditional statements known as **“If-Then”** rules.

2.8.1 “If-Then” Fuzzy Statement Rules

The purpose of fuzzy logic is to map an input space to an output space, and the primary mechanism for doing this is a list of “IF – THEN” statements called rules, placed between the input space and output space.

A Fuzzy rule is a conditional statement R_k based on expert knowledge expressed in the form of fuzzy equation (2-5):

$$R_k: \textbf{IF } x \text{ is } A \textbf{ THEN } y \text{ is } B \qquad (2\text{-}5)$$

Where A (e.g. small) and B (e.g. large) are linguistic values defined by fuzzy sets, on the range (universe of discourse) x and y respectively. R_k is the k^{th} rule.

If there are n rules, the rule set, R, is represented by the union of the rules in the form of the fuzzy equation (2-6).

$$R = R_1 \text{ else } R_2 \text{ else } R_3 \text{ else } \dots R_n. \qquad (2\text{-}6)$$

The **“IF”** part of the rule **“x is A”** is called **antecedent** or **premise**. The **“THEN”** part of the rule **“y is B”** is called the **consequent** or **conclusion**. In general, the input to an if-then rule is the current value for the input variable, U (universe of discourse), and the output is an entire fuzzy set, **μ ([0, 1]**).

Interpreting if-then rules is a three-part process: **Fuzzy inputs -** Resolve all fuzzy statements in the antecedent to a degree of membership between 0 and 1. **Apply fuzzy operator** to multiple part antecedents and resolve the antecedents to a single number between 0 and 1. **Apply implication method-** use the degree of support for the entire rule to shape the output fuzzy set.

If the antecedent is true to some degree of membership, then the consequent is also true to the same degree. Thus in binary logic: if $p \rightarrow q$ (here p and q are either both true or both false). In fuzzy logic: if $0.4p \rightarrow 0.4q$ (here partial antecedents provide partial implication). The "implication function" then modifies that fuzzy set to the degree specified by the antecedent.

In general, one rule alone is not effective. Two or more rules that can play off one another are needed [12].

2.8.2 Fuzzy Inference Systems

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic [12]. There are two types of fuzzy inference systems that vary somewhat in the way outputs are determined [12][24]: **Mamdani type:-** proposed in 1975 by Ebrahim Mamdani - the output membership functions are single spike fuzzy sets (singleton outputs) rather than distributed fuzzy sets. Mamdani method finds the centroid of the two-dimensional output function for defuzzification purpose. **Sugeno type:-** used to model any inference system in which the output membership function are either linear or constants [12].

Mamdani method Fuzzy inference process comprises of five parts: first step is **fuzzification** of the input variables where the degree to which they belong to each of the appropriate fuzzy sets via membership functions is determined. The second step is application of the **fuzzy operator** (AND or OR) in the antecedent. The fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. The third step is **implication** from the antecedent to the consequent. The rule's weight must be determined first. The forth step is **aggregation** of the consequents across the rules the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. The fifth step is **defuzzification** where a single crisp number is determined by centroid method of the aggregate.

This fuzzy inference process could best be explained in a diagram as in figure 2.10 [12].

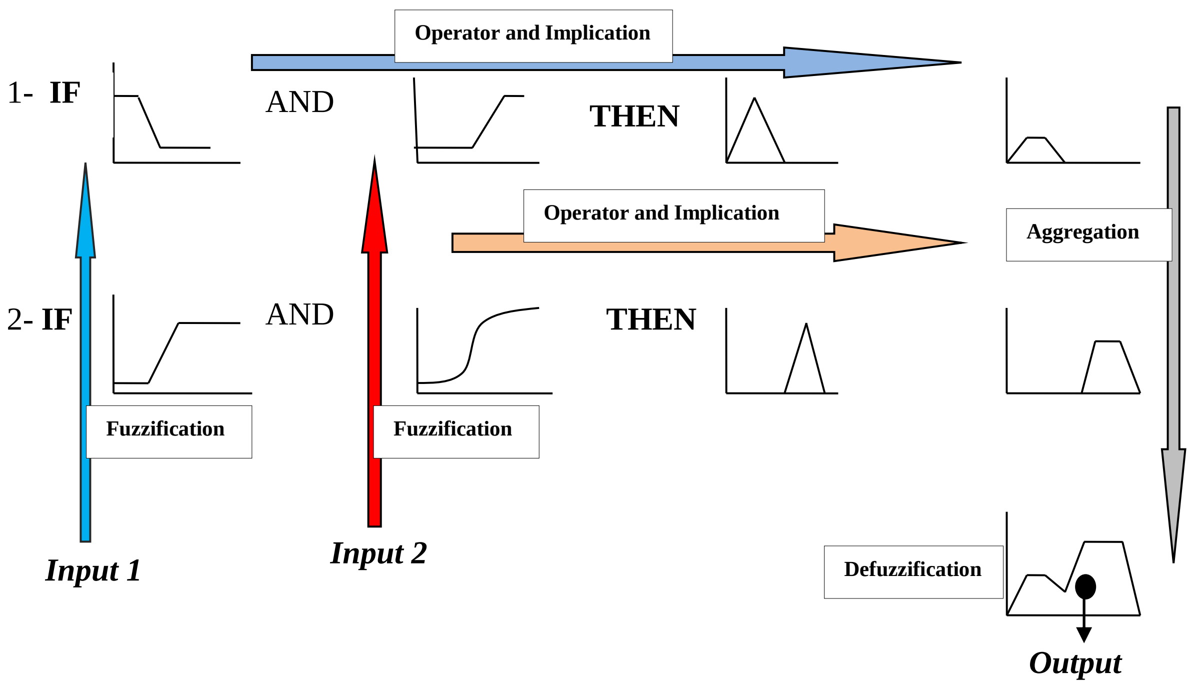


Figure 2.10: Fuzzy inference process diagram

In this figure 2.10, the flow proceeds up from the inputs in the lower left, then across each row, or rule, and then down the rule outputs to finish in the lower right.

The most popular defuzzification method is the centroid calculation, which returns the center of area under the aggregated curve.

2.9 Lighting Systems with Fuzzy Logic controls

In a paper by S.D. Panjaitan [1], fuzzy logic scheme is proposed as a basis to control lighting system in building zone where the fluorescent lamps are the controlled objects. The proposed lighting design procedure determines the maximum number of lamps that should be used according to the room function. Then the proposed controller is activated and deactivated according to information from occupancy sensors, which gives information about room occupancy. The fuzzy set of the output variable is defuzzified to deliver a crisp numerical value by the centroid-of-area method. Programming of the Fuzzy Logic Controller for the lighting control system was realized by using Software Assembler DT51S.

Papers by [1], [22] and [29] describes the development of fuzzy logic controller for room lighting system using a microcontroller. Input to the fuzzy logic controller is room light level and the outdoor daylight level and the number of occupants in the room. The controllers will control daylight shading, and the number of lamps to be switched on while maintaining the suitable illuminance for the specific condition of the room. The paper by M.A.A. Saleh [29] describes a fuzzy controller that controls the number of lamps lit using the number of people inside the room and the required illuminance as control inputs.

M. T. Lah [18] proposed a modern approach to control the inside illuminance with fully automated fuzzy system for adjusting shades, which responds constantly to the changes in the available solar radiation, which makes decisions as it follows the human thinking process. The control algorithm contains a cascade control with fuzzy controller as the main and conventional PID-(proportional-integral-derivative) controller as auxiliary controller. The implementation of fuzzy logic controller for the roller blind positioning is Sugeno type.

C. Zhang [28] developed a microprocessor-based intelligent control device for streetlight control, applying fuzzy decision theory to distinguish accurately various interferences and to make it operate, reliably, a transformer high voltage circuit breaker.

The paper by M. L. Jin [2] describes how we can design a lighting control system including hardware and software based on fuzzy logic. Software incorporates LABVIEW graphical programming language and MATLAB Fuzzy Logic Toolbox to design the light fuzzy controller. The control system can dim the bulb automatically according to the environmental light. The fuzzy set of the output variable is defuzzified to deliver a crisp numerical value by the center-of-gravity method.

K. K. Tan [13], S. Mehan [14] and C. M. Prades [31] describes the implementation of an intelligent traffic lights control system using fuzzy logic technology which has the capability of mimicking human intelligence for controlling traffic lights. The papers [13][14][31] proposed fuzzy logic controlled traffic light that uses sensors that count the numbers of cars in a queue and extend or reduce time needed for the green light on the arrival side. The reasoning method in the fuzzy controller is similar to that of a policeman handling the traffic flow at a typical junction.

K. Alexandridis [23] proposed a control method that uses digital PI-like fuzzy logic controller to improve both lighting level and energy efficiency at the same time. Hybrid systems like ANFIS (Adaptive Neuro-Fuzzy Inference System) was used for prediction and control of the artificial lighting in buildings, following the variations of the natural lighting. The indoor illuminance levels together with the Daylight Glare Index are taken into account by the fuzzy control scheme to regulate the shading and electric lighting.

M.G. Shafer [32] proposes a model of fuzzy logic control system to control illumination of LEDs lamp, in order to obtain homogeneity of light intensity in a room.

2.10 Summary of the Literature Review

The literature described various sources of light and why quality of the light is more important than its quantity in illuminating a space. To achieve a desired quality of light for a space, various control models are described, including DALI and Fuzzy Logic Controllers. Electrical energy saving has been identified as the major concern in designing any intelligent and efficient lighting system.

However, the author noticed a need in research for an intelligent lighting system that takes advantage of availability of daylight and the new generation of high efficient RGB LEDs in production of both white light and multi-coloured light. The author proposed a design of a multi-coloured lighting system, based on Fuzzy Logic, where the electric light source changes its light intensity and colour automatically to the desires and convenience of the user.

2.11 Concept Design of an Intelligent Multi-Coloured Lighting system

Figure 2.11 is a block diagram illustrating the concept of a lighting system with fuzzy logic controller. It explains the process of automating multi-coloured LEDs lighting intensity and colour change in a room. The proposed system has five inputs and four outputs.

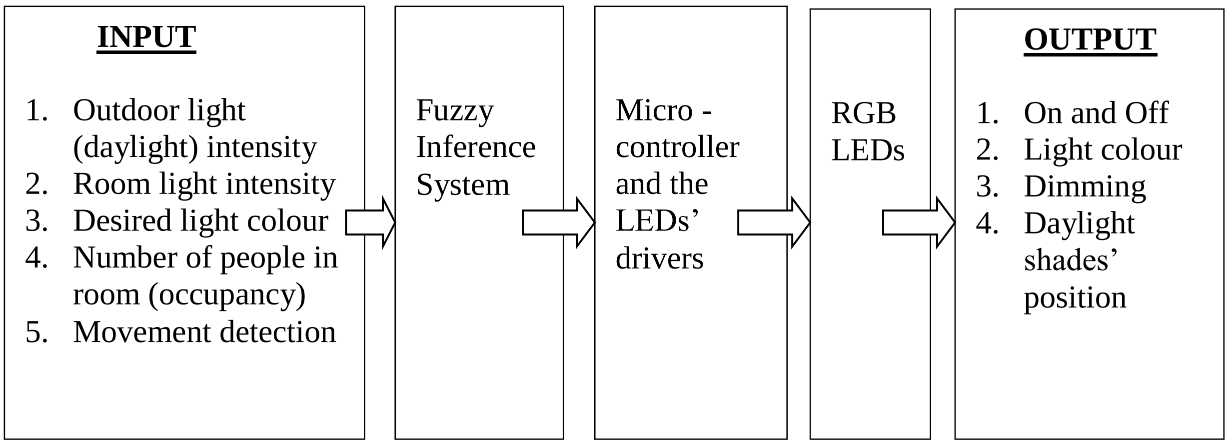


Figure 2.11: Concept design of a multi-coloured lighting system with fuzzy logic controller

The input **"Daylight"** refers to the natural outdoor light from the sun as detected by a light sensor: If the daylight intensity level is at the required minimum setting, the room's sun light window shades (blinders) automatically opens to maximum position possible. If the daylight intensity is lower than minimum set point, the shades closes.

The input **"room light intensity"** refers to the lighting level in the room area or space as measured by the installed photometer (light sensor): This determines the dimming of the LED's light. If the light level is higher than the set point, the LEDs automatically dim down to the required room light level. If the light level in the room is lower than the set point, the sun shades are opened further, but if the sun shades are fully open and the room light level is still low, the LEDs output light is increased. If the room light level is higher than the set point and the LEDs are fully dimmed, then the shades are automatically partially closed.

The input **"Desired room light colour"** refers to the user's preferred colour as selected on a touch pad colour chart or colour sensor or mood detector: The light produced by the LEDs will be of the colour as the selected by the user on a colour chart touch pad or detected colour/mood. If the selected colour is **not white**, then the room's window outdoor light shades will automatically close fully.

The input **"room occupancy"** is same as **"number of people in the room"** which is the number of people occupying the room as computed by an entrance counter detector: If the computed number of persons in the room is one or more, then the LEDs system will automatically be activated to normal operation. If the computed number of persons is zero, then the LEDs light will automatically be dimmed off.

The input **"movement detection"** refers to motion sensors detecting movement in the room: If the motion sensors do not detect movement in the room within a predetermined duration, then the LEDs light is dimmed off. If a movement in the room is detected, then the LEDs system is activated to normal operations.

CHAPTER 3 - MATERIALS AND METHODOLOGY

3.1 Introduction

How the research was performed is briefly explained in this chapter. A line diagram representing a typical room is described, where the indoor room illumination is the subject of control. The general functionality of the multi-coloured lighting system is shown in a labeled single line diagram. The functions and the principles of operation of each component in the lighting system are also described. Also shown is schematic diagram with hardware that may be used in implementing the lighting system.

MATLAB computer software environment is used for simulating operations of the lighting system. Screenshot of the assembled MATLAB Simulink model of the multi-coloured lighting system is shown. Also outlined here are the operational assumptions for the simulation. Screenshots of the membership function plots and the "IF-THEN" statement control rules for two Fuzzy Logic Controllers are explained.

The function and purpose of each section of the MATLAB-Simulink lighting system model is explained with aid of sectional screenshots. The simulation processes and points for monitoring the lighting signal levels and the LEDs' current pulses are explained.

3.2 Typical Room Representation Diagram with Lighting Control Infrastructure

The figure 3.1 is a labeled diagram representing a typical room whose inside illumination level is controlled by light from a set of ceiling mounted multi-colour LED lamps and daylight (outdoor light) through clear-glass window with electrically movable shades (outdoor light blinders). It is assumed that the number and the rating of the multi-colour LED lamps is enough to illuminate the whole room uniformly and to the required light intensity. It is also assumed that the windows are large enough to allow passage of the daylight to illuminate the room uniformly to the required light intensity. The window shades are expected to blind out the outdoor light. The amount of outdoor light entering the room is expected to be proportional to the opening of the window shades. Opening of the window shades is electrically controlled.

There is only one indoor light sensor, which is ceiling mounted at centre of the room. The outdoor light sensor is strategically mounted to monitor the daylight levels that could pass through the window into the room. The movement detector is mounted in front side of the room in a position such that it can detect motion of persons in the entire room space. The room occupancy counter is composed of two detectors that are conveniently mounted sequentially at the door frame such that the first detector in entering is assigned addition to number in the room, and other detector on the line, which is first in leaving the room, is assigned subtraction to the number in the room. The colour selector/sensor/decoder module is mounted conveniently at the entrance area of the room such that the user has an option of either select a colour by touch of a colour-chart or the module can sense a facial mood of a person or the module can decode clothing colour and automatically set the colour of the LED lamps. The colour signal is expected to determine the window-shades' opening position. Figure 3.2 is the flow chart for signal controlling the lighting system.

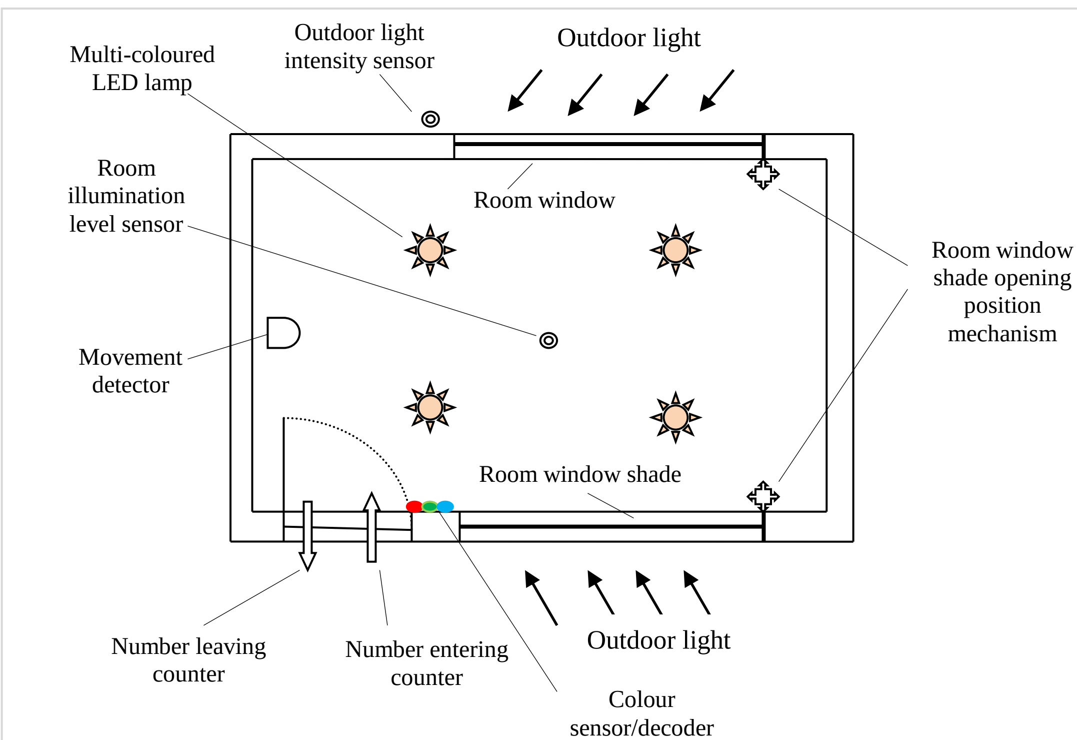


Figure 3.1: Illustration of a typical room with controlled multi-coloured LED lighting

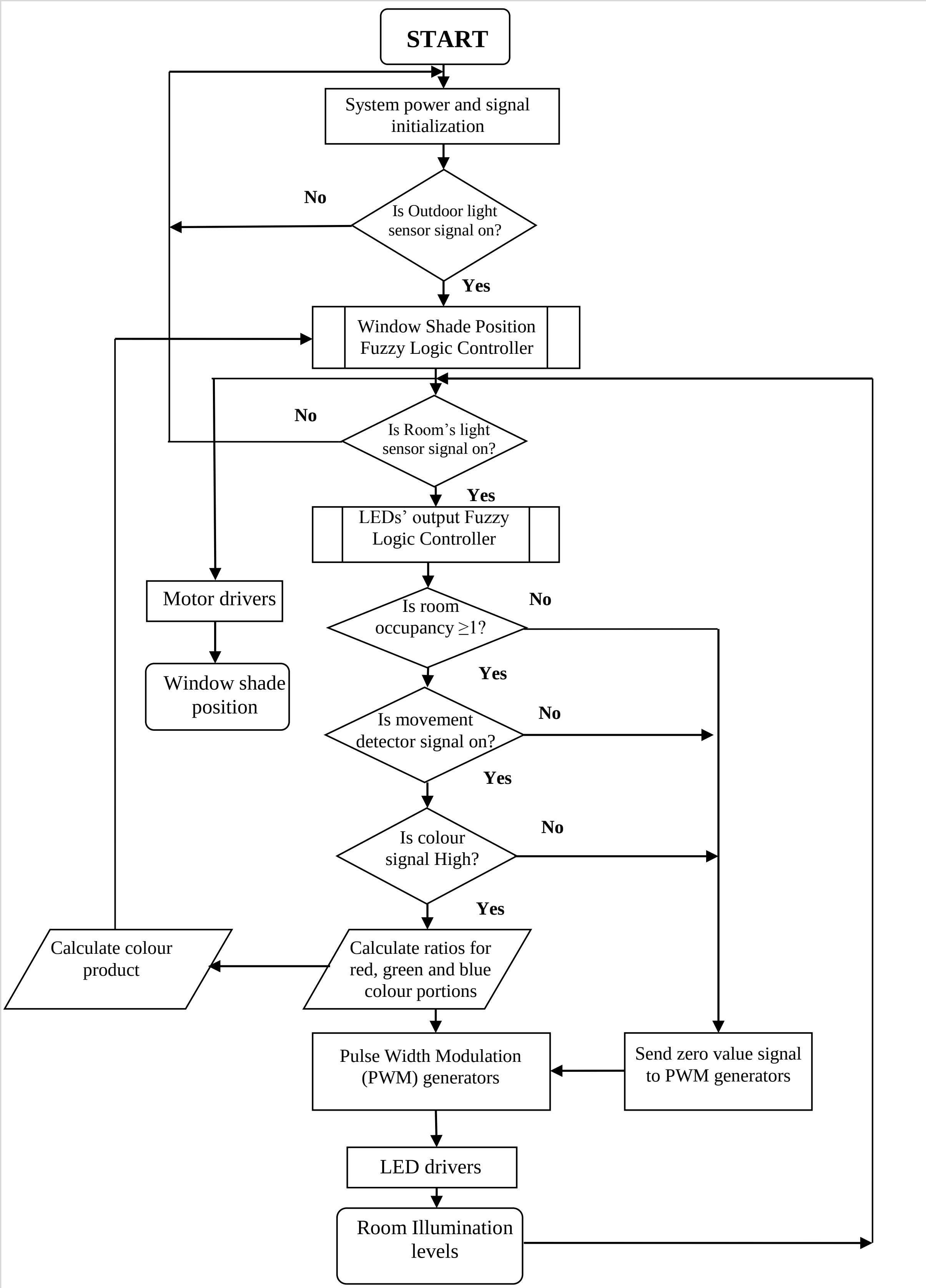


Figure 3.2: Signal flow chart for controlling the lighting system

3.3 Functional Block Diagrams for the Lighting System Model

3.3.1 Functional Representation of the Lighting System Model

Figure 3.3 shows basic scheme of the multi-coloured lighting system with two fuzzy logic controllers; one for controlling position of the window light-shade opening (position) and the other for controlling the average output light intensity (luminance) of the multi-colour LEDs.

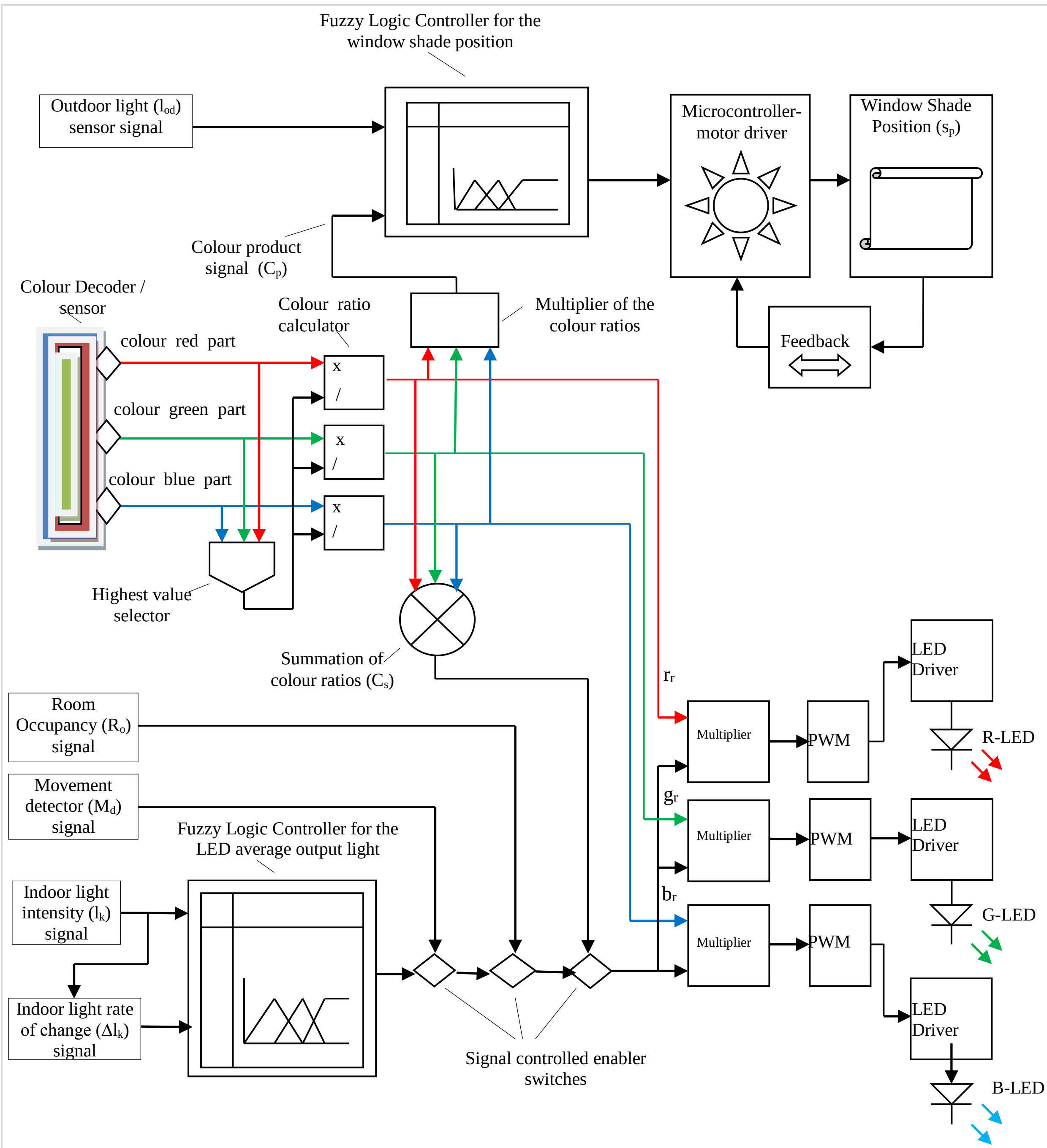


Figure 3.3: Basic scheme of the multi-coloured LED lighting system

The multi-coloured lighting system is based on Fuzzy Logic controllers which enable it have the necessary operational intelligence that mimic human decision making process. Daylight (outdoor lighting) harvesting through windows with controllable window-shade mechanism was necessary for reducing use of electrical energy. The system uses multi-colour (RGB) LEDs for purpose of producing dynamic coloured light in a typical room space.

3.3.2 Physical Implementation schematic diagram

Figure 3.4 is a labeled schematic diagram with actual industrial electronic devices proposed for implementing the multi-colour LEDs room lighting system. All the lighting system actual devices are digitally addressable and are expected to intercommunicate through the I^{2}C (Inter-Integrated Circuit) bus. The software for the Fuzzy Logic Toolbox and the colour decoder signal processing, would be installed in the master microcontroller.

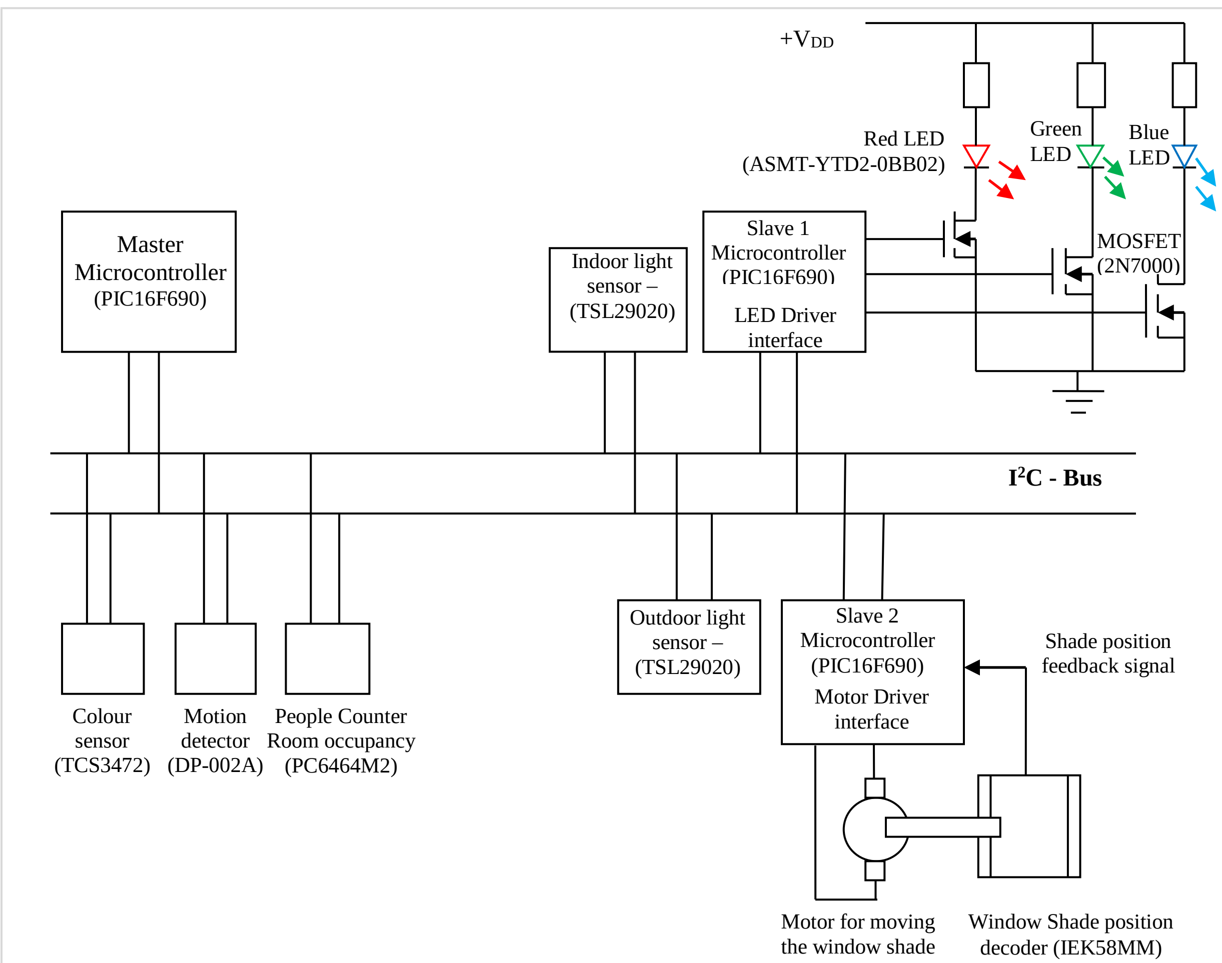


Figure 3.4: Schematic diagram for implementing the LED lighting system

The various actual devices that may be used in constructing (implementing) the multi-coloured lighting system are described in the table 3.1 for list of items.

Table 3.1: List of the actual physical devices for realizing the lighting system

Item	Description	Manufacturer	Part No./Type	Remarks
1	Master microcontroller	Microchip Technology Inc. USA. http://www.microchip.com	PIC16F690	Master Microprocessor
2	RGB LEDs	AVAGO Technologies, USA http://www.avogotech.com	ASMT-TYD2-0BB02	PWM driven
3	Microcontroller – PWM generator for the LEDs' drivers and the Shade position motor drive	Microchip Technology Inc. USA. http://www.microchip.com	PIC16F690	Serial addressable device through I^2C Bus
4	-Indoor light sensor -Outdoor light sensor	Texas Advanced Optoelectronic Solution (TAOS) Inc. USA http://www.taosinc.com	TSL29020	Digital addressable devices.
5	Window Shade position decoder	TR-Eletronic GmbH, German http://www.tr-electronic.de	IEK-58MM (Integrated Coupling Incremental Encoder)	Digital addressable device
6	Colour sensor	Texas Advanced Optoelectronic Solution (TAOS) Inc. USA http://www.taosinc.com	TCS3472	Digital addressable device
7	Motion detector	Glolab Corporation, USA http://www.glolab.com	DP-002A	Digital addressable device
8	Room Occupancy counter (People counter)	IEE, Luxembourg Web: www.iee.lu	PC6464M2	Digital addressable device

3.4 LED Driver

LEDs are current driven devices. Figure 3.5 shows the characteristic curve of a LED [1]. The y-axis is the current, in mA, through the LED while the x-axis is DC voltage, in volts, across the LED. By increasing the voltage in the ΔV range, the current increases almost proportional.

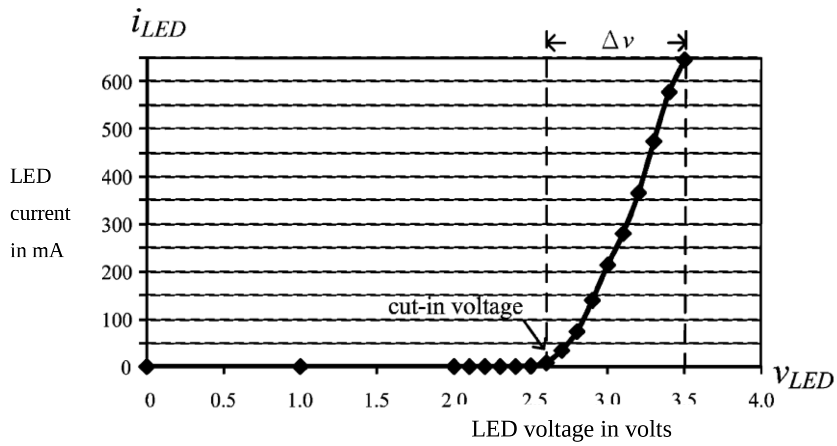


Figure 3.5: LED characteristic curve [3].

The brightness of an LED is approximately proportional to its average current. However, a current variation in an LED may cause colour shift. Such an approach is not appropriate for applications, which strictly requires a consistent colour gamut [3]. For this reason a driver circuit is designed essentially to drive LEDs at the required constant current.

To prevent the LED lighting from colour shift, the LED lamp can be dimmed by pulsed current. The average LED current is adjusted by the duty cycle of the PWM.

Figure 3.6 shows a LED circuit with a pulse controlled switching device. The switching device (LED driver) is fed with a controlled signal from a PWM pulse generator. The average load current I_o is a function of the duty cycle of the PWM for controlling opening and closing of the circuit switch S. The resistor R is for limiting the current amplitude.

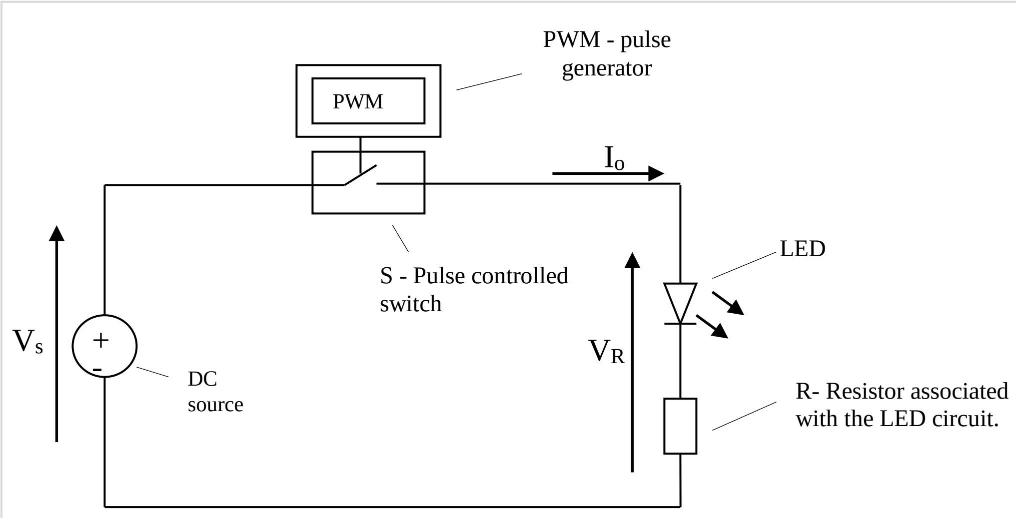


Figure 3.6: PWM controlled LED circuit

When switch S is closed, the current, I_o, rises instantaneously to V_s/R. When switch S is opened, the current at once falls to zero.

Figure 3.7 shows the theoretical wave form of the voltage across the associated LED resistor, V_R, and the current I_o. The voltage, current and power delivered to the LED is represented by equations (3-1) to (3-7).

A chopped dc voltage is produced in the LED resistor terminal:

$$V_R = T_{ON}/(T_{ON} + T_{OFF})V_s = T_{ON}/T\ V_s = \alpha V_s \qquad (3\text{-}1)$$

Where $T=T_{ON} + T_{OFF}$ = chopping period.

$\alpha = T_{ON}/T$ = duty cycle (duty ratio)

Thus, the LED and resistor average voltage, V_o, can be controlled by varying the duty cycle α.

$$\text{Average output voltage } V_o = \alpha V_s \qquad (3\text{-}2)$$

$$\text{Average output current } I_o = \alpha V_s /R \qquad (3\text{-}3)$$

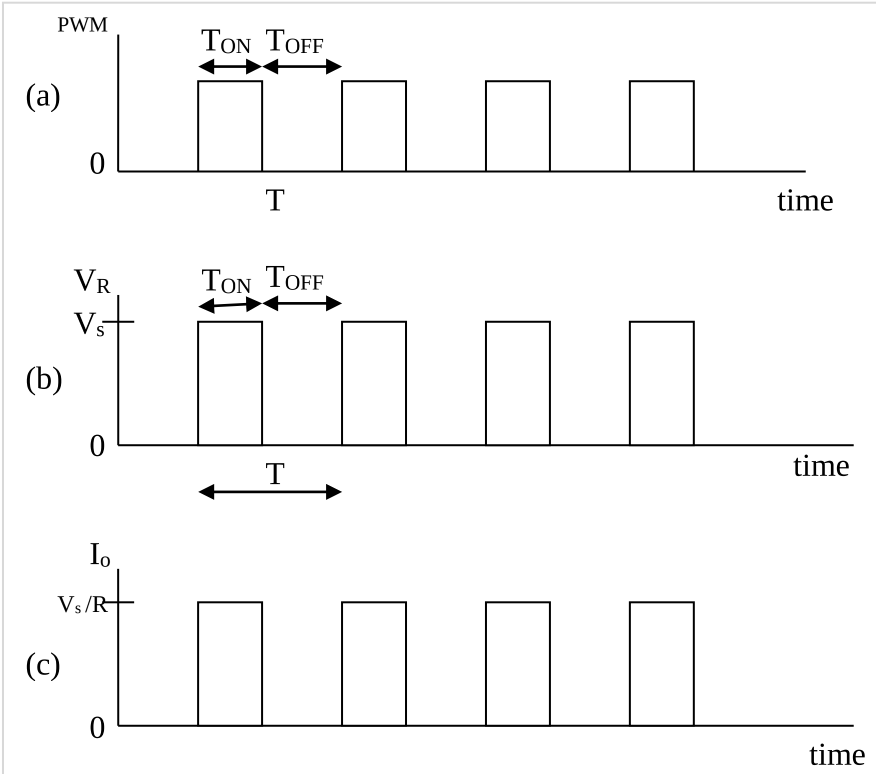


Figure 3.7: Theoretical Pulse wave forms – (a) PWM generator output, (b) voltage V_R across the resistor, (c) current I_o through the LED.

Calculation of the RMS values and the average power consumed by the LED.

RMS value of output voltage $V_{or} = [\alpha V_s^2]^{1/2} = \sqrt{\alpha}\, V_s$ (3-4)

RMS value of output current $I_{or} = [\alpha (V_s/R)^2]^{1/2} = \sqrt{\alpha}\, (V_s/R)$ (3-5)

Power delivered to the LED $P_o = I_{or}\, V_{or} = \sqrt{\alpha}(V_s/R)\, \sqrt{\alpha}\, V_s = \alpha\, (V_s^2/R)$ (3-6)

Hence, $P_o = K\alpha$ (3-7)

Where K is a constant, (V_s^2/R), as long as the dc source, V_s, is maintained constant.

The average power P_o through the LED resistor is controlled through α (duty cycle) by opening and closing the switch S periodically by means of the PWM pulse generator. The P_o is proportional to the LED's luminosity level.

A means to control the duty cycle, α, of the PWM pulse generator output is all what was required.

3.5 PWM - Pulse Generator

A Pulse Width Modulator (PWM) generator is a device which is a source of control signal of pulses with constant amplitude and frequency but variable duty cycle.

The reference signal, called modulating signal, is naturally sampled and compared with a symmetrical triangle carrier as shown in figure 3.8, graphical representation. A PWM generator block, used in MATLAB Simulink computer software, has two output signal; pulse-upper device level (high=1) and pulse-lower device level (high=1). When the reference signal is greater than the carrier, the pulse for the upper switching device is high (1), and the pulse for the lower device is low (0).

The triangular carrier wave is used to fix the frequency of the output pulses.

For uniformly generated rectangular output pulses, a constant input signal is used as reference. The output pulse width (the duty cycle) is varied by varying magnitude of the input signal as demonstrated in figure 3.8 and figure 3.9 wave forms. Part (a) of figure 3.9 shows the triangular carrier wave form cross-cut with constant reference signals, one with value more than zero and another with value less than zero.

Part (b) of figure 3.9 shows two sets of the generator out pulses with same period T; one with wider $\mathbf{T_{ON}}$ duration as a result of the input reference signal of value more than zero (signal line of colour blue). The other pulse has a narrow $\mathbf{T_{ON}}$ duration which results from an input reference signal of value less than zero (signal line of colour red). The narrow pulses are also shown in part (c). Width of the output pulses is proportional to the value of the input signal in the range of -1 to +1.

An appropriate source of signal to control the duty cycle of the PWM generator was required.

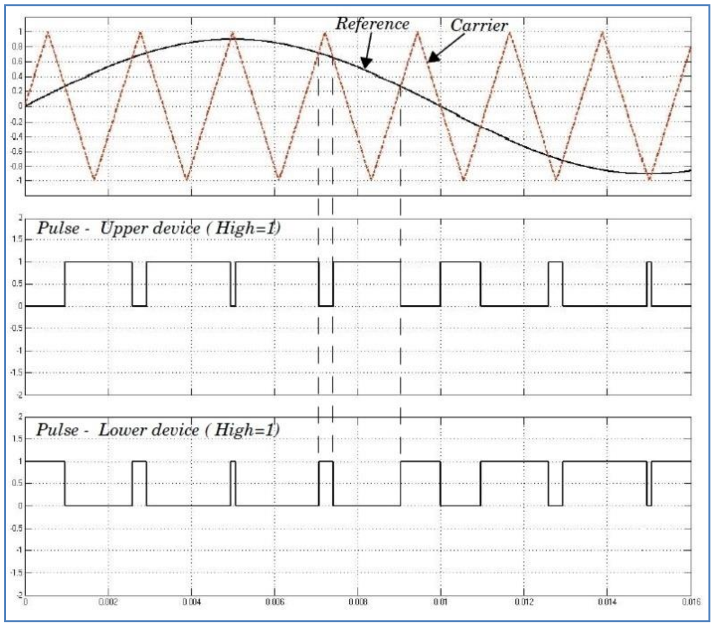


Figure 3.8: PWM Generator (2-level) wave forms – (a) the reference and the triangular carrier, (b) the upper device output pulses, (c) the lower device output pulses.

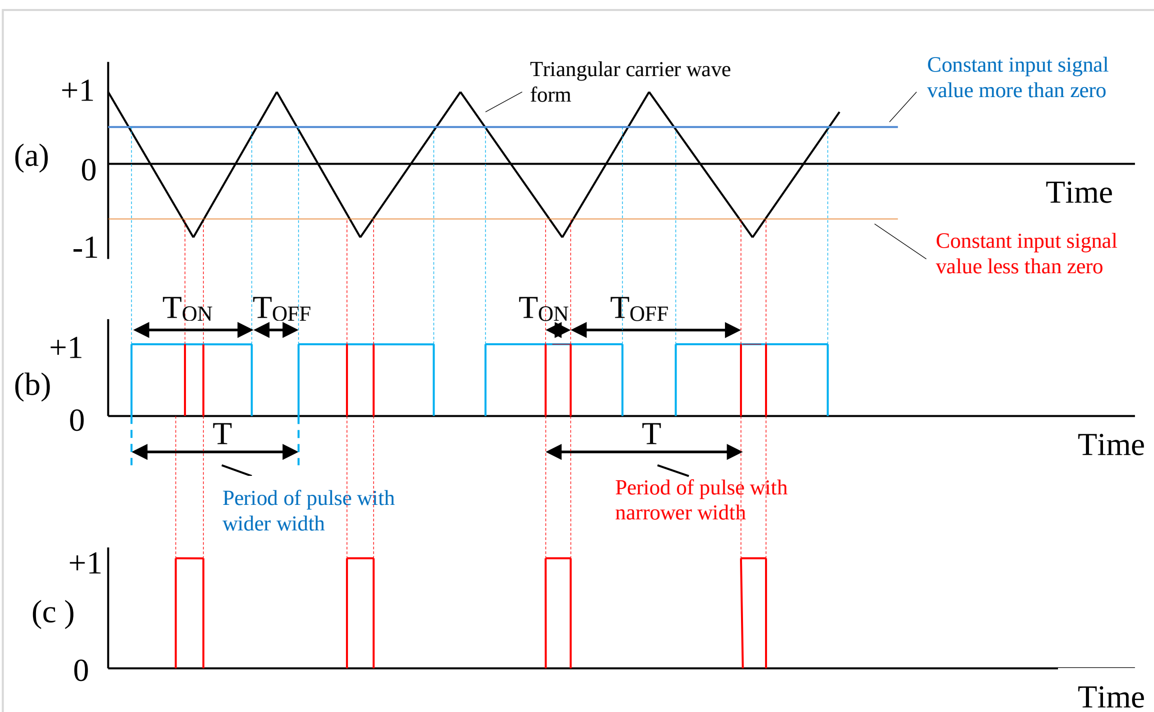


Figure 3.9: PWM generator - Illustration of pulse generation; (a) input reference signals, (b) output pulses (c) Narrower pulse with PWM generator reference input value less than zero

3.6 Signal Source Controller

The signal level which is input to PWM generator, for variable output pulse width, requires control. The indoor light sensor output signal, was identified as the initiator that affect the required LEDs output. An appropriate controller was required to be between the indoor light level sensor and the PWM pulse generator. The controller output signal level was required to be variable values in the range of **-1** to **+1,** as input to the PWM generator.

There are several types of controllers that would be used.

3.6.1 Conventional Controllers

The conventional controllers like PIDs, PLCs, digital signal controllers, microcontrollers, digital signal processors were considered. Each of the conventional controllers was found to be heavily dependent on complex software programming.

A digital signal controller (DSC) is a hybrid of microcontrollers and digital signal processors (DSPs). Like microcontrollers, DSCs have fast interrupt responses, offer control-oriented peripherals like PWMs and watchdog timers, and are usually programmed using the C programming language, although they can be programmed using the device's native assembly language. DSCs are used in a wide range of applications, but the majority goes into motor control, power conversion, and sensor processing applications. Currently DSCs are being marketed as green technologies for their potential to reduce power consumption in electric motors and power supplies.

3.6.2 Fuzzy Logic controllers

Fuzzy logic controllers are fashionable in areas of artificial intelligence like in sense and control of intelligent systems. The controllers rely on expertise knowledge and desires of the system user. Very little programming is required. It is easier to program the controller using the already packaged software, Fuzzy Logic Toolbox, in MATLAB computer software environment.

Fuzzy Logic control system was chosen as the most appropriate controller for the lighting system due to its simplicity, generalization of light level settings, and auto-control ability.

A basic configuration of a two input fuzzy logic controller is illustrated in figure 3.10. The U_1 and U_2 in the diagram represent the first and the second input signals respectively. The output signal of the controller is a crisp value that may be used as reference (input) for the PWM pulse generator.

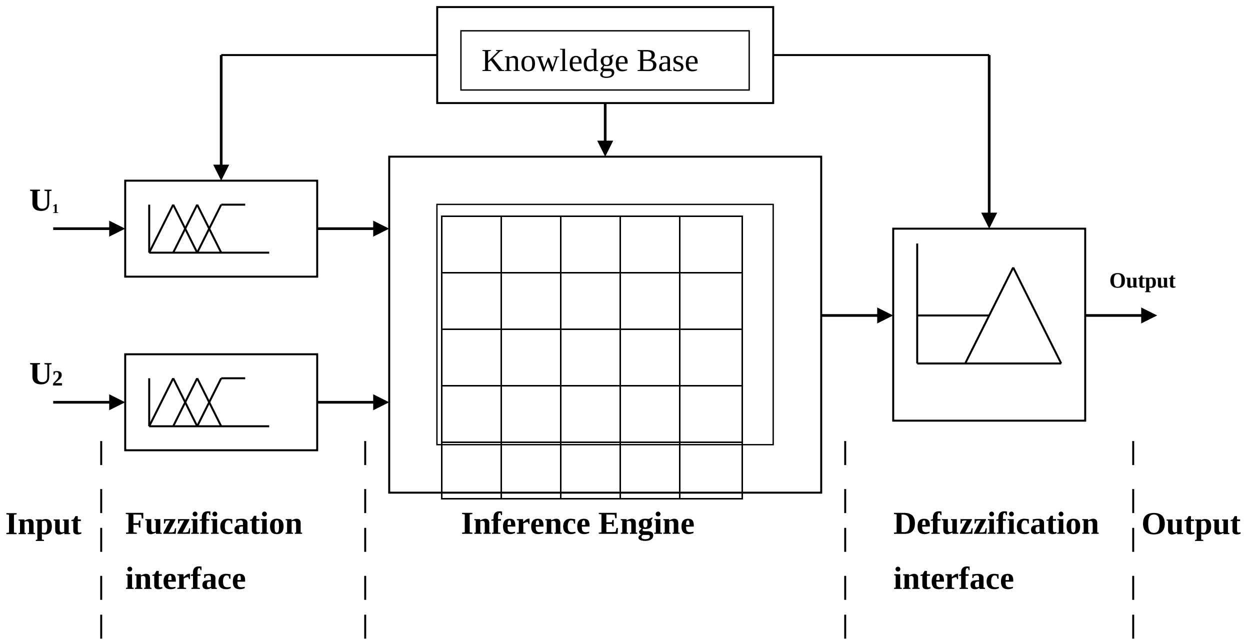


Figure 3.10: Illustration of basic principle of Fuzzy Logic Controller

The fuzzy logic controller comprises of four principal components:

1. **Fuzzification Interface:-** It converts input into suitable linguistic values using a membership function.
2. **Knowledge base:-** Consists of a database with the necessary linguistic definitions and the control rules.
3. **Inference Engine:-** It simulates a human decision making process in order to infer the fuzzy control action from the knowledge of the control rules.
4. **Defuzzificztion interface:-** Converts an inferred fuzzy controller output into non-fuzzy (crisp) control action signal.

3.7 Light Colour Production

The primary colors of light are red, blue, and green. The secondary are yellow, cyan, and magenta. When beams of light are mixed without any absorption, an additive process occurs. The more we mix the beams, the closer they get to being white light. Figure 3.11 demonstrates the additive colour mixing.

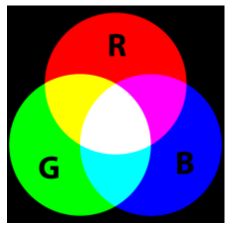


Figure 3.11: Additive colour mixing demonstration

The average current through each LED determines its output luminance level, which is its ratio contribution to the total output light colour. By controlling the average current through each colour LED, any colour could be created. This is illustrated in figure 3.12.

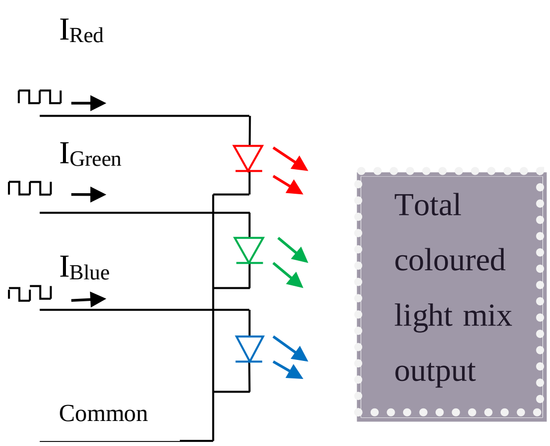


Figure 3.12: RGB LED scheme circuit diagram – output coloured light production

The three coloured LEDs were expected to be physically close and next to each other so that their output light blends well. The average current to each colour LED is expected to be a fraction of the highest of the three. To ensure that the average current to any two of the coloured LEDs is a fraction of the one with highest value, a colour decoder circuit is configured that first identify the signal value of the highest dominant colour, then divide each colour portion signal with the highest value. Output of the configured colour decoder circuit is three signals, which are ratios for each respective primary colour.

The circuit connects the common control signal, from the Fuzzy Logic controller, to three multiplication parallel circuits, where the product signal controls duty cycle of each respective colour PWM generator as illustrated in figure 3.13, which shows the basic scheme for controlling the average current for each coloured LED.

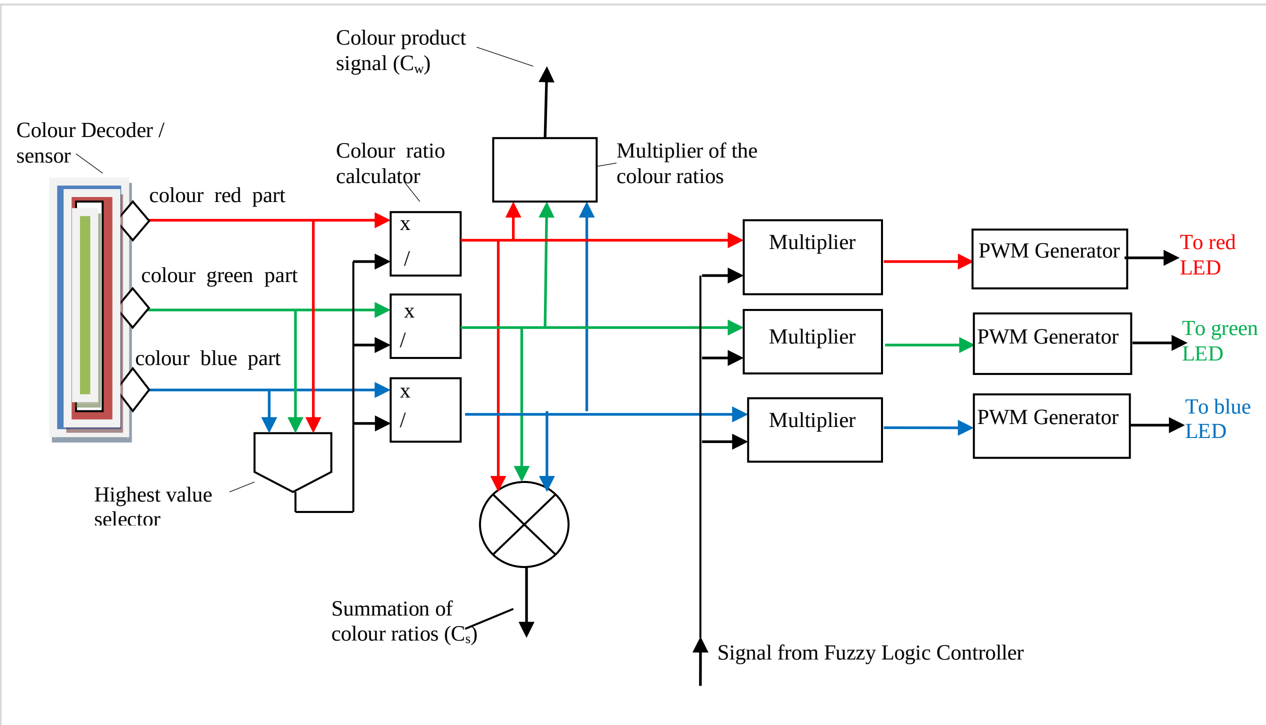


Figure 3.13: Basic scheme for colour product and LEDs respective PWM generator

The signal ‘colour product signal’ shown in figure 3.13, is product of the colour signal ratios and was used as input to window shade position fuzzy logic controller.

The signal ‘summation of colour ratios’ shown in figure 3.13, is sum of the three colour signal ratios and was used to operate an enabler switch in the LEDs Fuzzy logic Controller output signal circuit.

3.8 Modeling and Simulation of the Lighting System in MATLAB Simulink

The lighting system software model was assembled and tested using the Simulink tools (blocks) in MATLAB software environment. Screenshots showing the various parts of the model are explained. Algorithms for the fuzzy logic controllers are in form of membership function plots. The configured equivalent fuzzy membership functions are also shown with screenshots.

3.8.1 The assembled model

A screenshot of the fully assembled model, using Simulink blocks, is shown in figure 3.14.

The following was assumed for the model:

1. Daylight contribution to the indoor light (room illumination) is directly proportional to the window shade opening position.
2. Total sum of the three colour LEDs' output light is the only artificial light in the room and is directly proportional to the amount of electric lighting contributed for the room illumination.
3. The signal for controlling opening of the window shades is directly proportional to position of the shades and the amount of outdoor light contributing to the room illumination. i.e.

   Outdoor light to the room (L_{od}) = constant (k_{od}) x window shade position control signal (p_r) . This is represented by equation (3-8).

   $$L_{od} = k_{od}p_r \tag{3-8}$$

4. The sum total of the LEDs output light contributing to the room's illumination is directly proportional to the control signal for each respective PWM generator. i.e

   LEDs' light output (L_{LED}) = constant (k_{LED}) x sum of the signals for the PWM generators (S_{PWM}). This is represented by equation (3-9).

   $$L_{LED} = k_{LED}S_{PWM} \tag{3-9}$$

5. Total room illumination level (indoor light intensity) is sum of the outdoor daylight and the LEDs' sum total output light. i.e. as represented by equation (3-10).

Room illumination = outdoor light to the room + LEDs' light output

$$\text{Room illumination } (R_i) = L_{od} + L_{LED} = k_{od}p_r + k_{LED}S_{PWM} \tag{3-10}$$

6. Indoor light intensity sensor signal, which is the input signal to the LEDs Fuzzy Logic Controller, is the room illumination level measured one simulation cycle earlier. i.e

Indoor light intensity signal (L_k)= one simulation cycle delay of room illumination ($z^{-1}R_i$). This is represented by equation (3-11), where z^{-1} is unit delay in sampling.

$$L_k = z^{-1}R_i = R_{i-1} \tag{3-11}$$

7. The signal for rate of change of the indoor illumination levels is the difference between value of the room light intensity and the value of a one simulation time cycle delayed room light intensity signal. i.e. as in equation (3-12).

Rate of change of room illumination (ΔL_k) = Room light intensity signal value (R_{i-1}) – one simulation time delayed (previous) room light intensity value (R_{i-2}).

$$\Delta L_k = R_{i-1} - R_{i-2} \tag{3-12}$$

8. Outdoor light level signal results from an outdoor light intensity sensor output. In the simulation this outdoor light signal level was manually input. A preset signal generator was also be used as input to the window shade fuzzy logic controller.
9. The colour decoder/selector/sensor is a specially designed device which can produce three signals; one for level value of colour red, another for level value of colour green, and the other level value of colour blue. In the simulation, each colour portion level value constant was manually input.
10. Both the movement detector and the room occupancy signal values were also manually input.

Signal levels for each part on the model were monitored by means of connected scope-blocks (Sc …) as shown in the screenshot of the assembled Simulink blocks in figure 3.14.

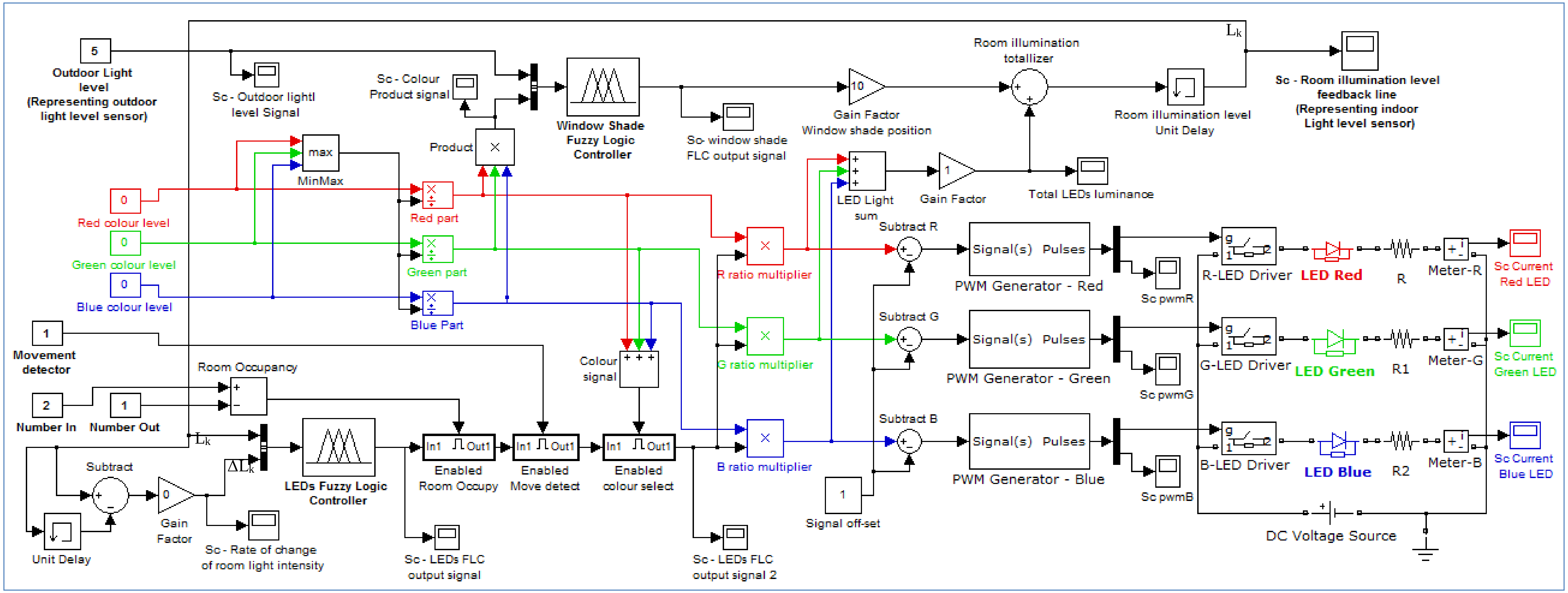


Figure 3.14: Screenshot of the assembled lighting system model in MATLAB Simulink

3.8.2 Window Shade Position Fuzzy Logic Controller - Functional Block

Figure 3.15 is a representation of the functional block for controlling the room's window shade opening position. Figure 3.16 is screen shot showing a section of the assembled model with simulink blocks that are used to simulate the functions of the window shade position fuzzy logic controller.

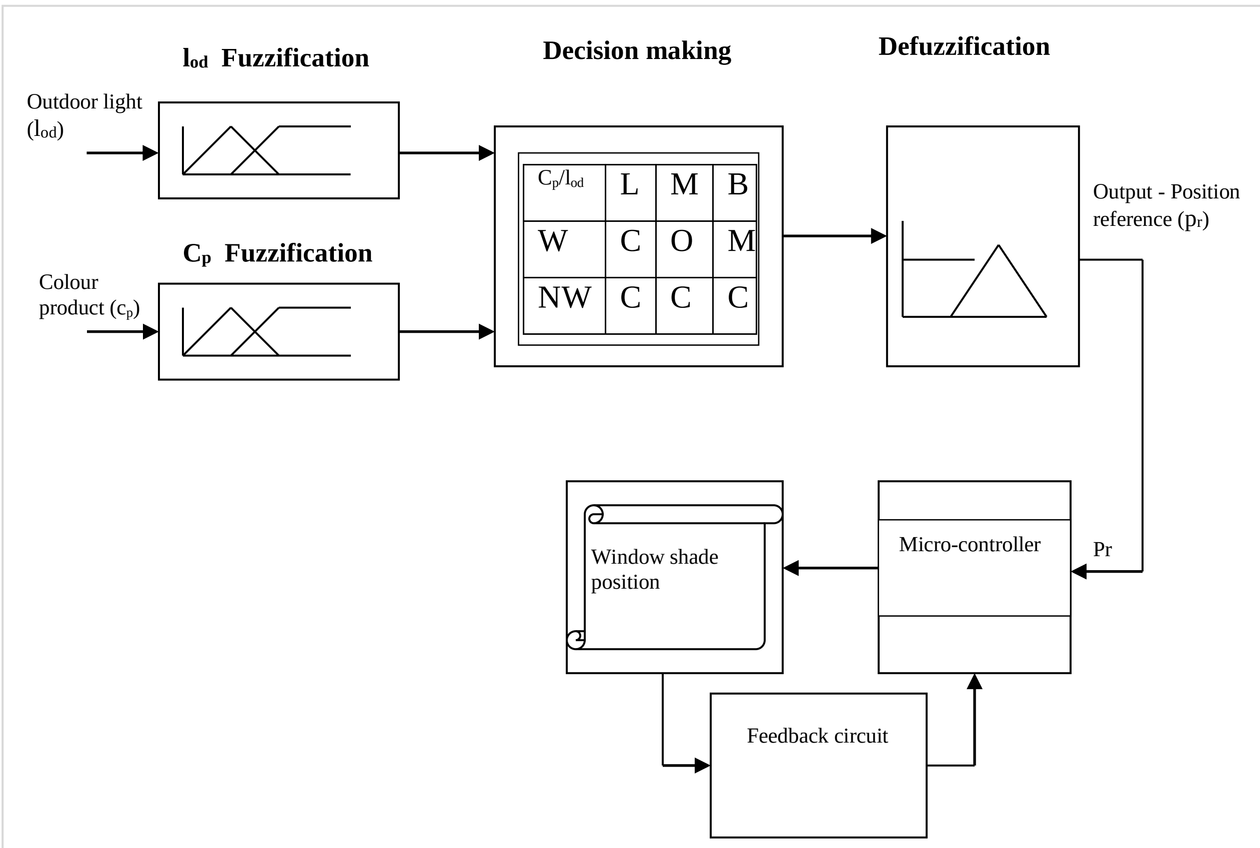


Figure 3.15: Window shade opening position fuzzy logic functional block

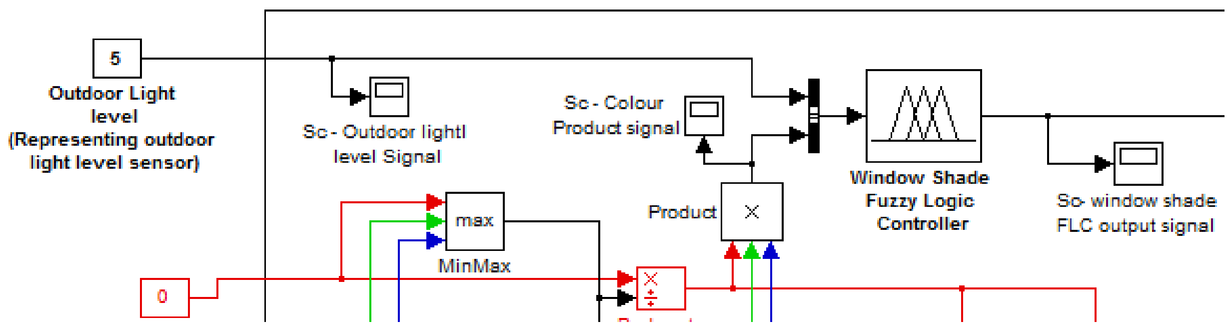


Figure 3.16: Simulink model screenshot- section for the window shade position fuzzy controller

The two inputs to the window shade opening (position) fuzzy logic controller are:

- Outdoor light intensity level signal
- Colour product signal – if the required LEDs output light colour is white or not white

The fuzzy inference system (FIS) was set in the MATLAB Fuzzy Logic toolbox. Figure 3.17 is a screenshot of the configured fuzzy logic inference system for the window shade position controller.

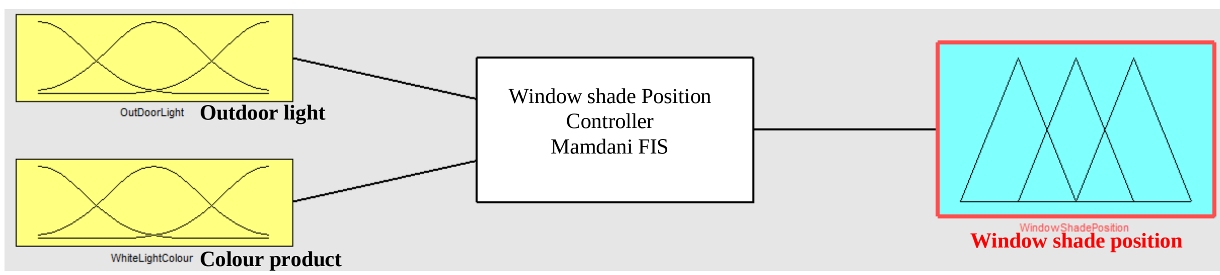


Figure 3.17: Screenshot of configured Fuzzy Inference System for window shade position

The selected Fuzzy Logic Inference system is Mamdani, where the output is a crisp single number based on the centroid moment of the aggregated output membership function.

Figure 3.18 shows the required membership function (algorithm plot) for fuzzification of the input l_{od}, outdoor light level. The input range is on scale of 0 to 10 for convenience in the test.

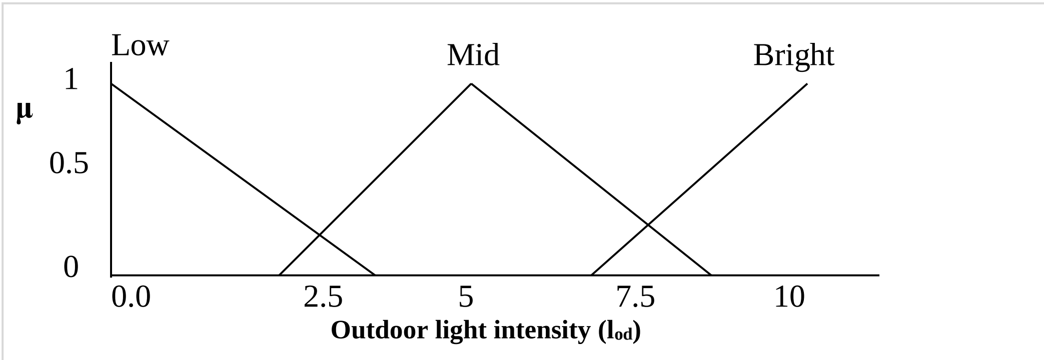


Figure 3.18: Outdoor light level input – Membership function algorithm plot

This membership function was configured in MATLAB Fuzzy Logic toolbox and the system membership function is shown by screenshot in figure 3.19. The Universe of Discourse, which is the x-axis, range from 0 signal value to 10 signal value for convenience of the tests.

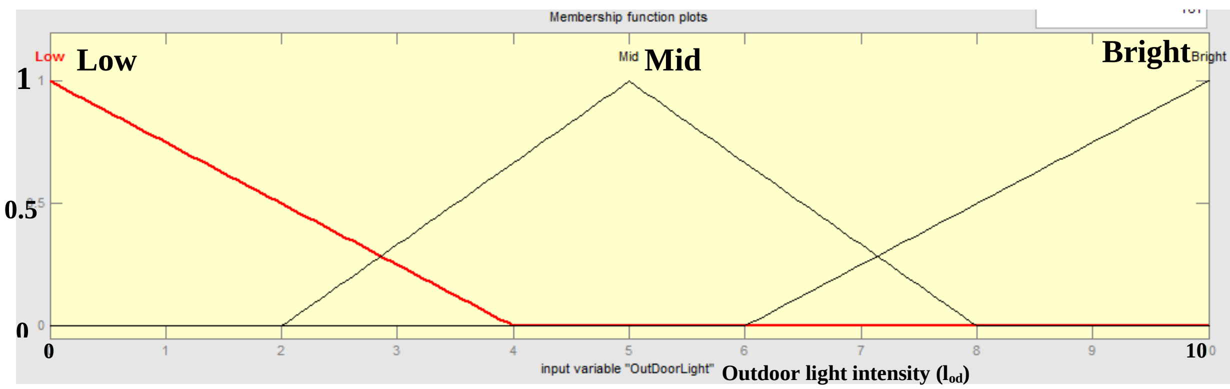


Figure 3.19: Screen shot of configured input Membership Function for outdoor light level

Figure 3.20 shows the required membership function (algorithm plot) for the input colour product signal c_p. The Universe of Discourse, which is the x-axis, range from 0 signal value to 1 signal value, convenient for the light colour product range. For convenience the, light colour is considered white if the colour parts ratio product is between 0.85 and 1. Light colour is considered as either white or not white. Figure 3.21 is screenshot of the configured membership function.

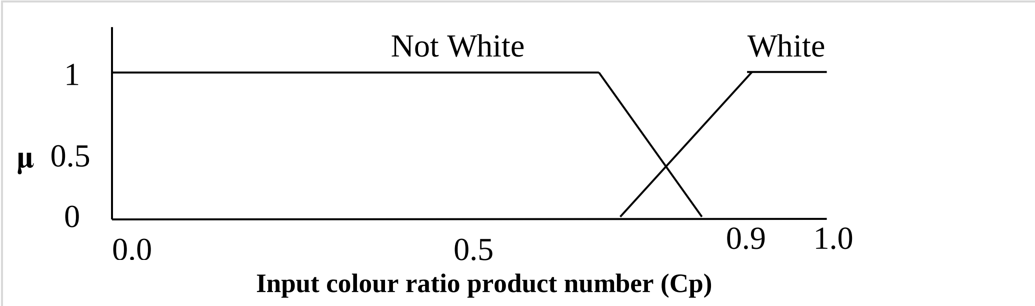


Figure 3.20: White light signal – Membership function algorithm plot

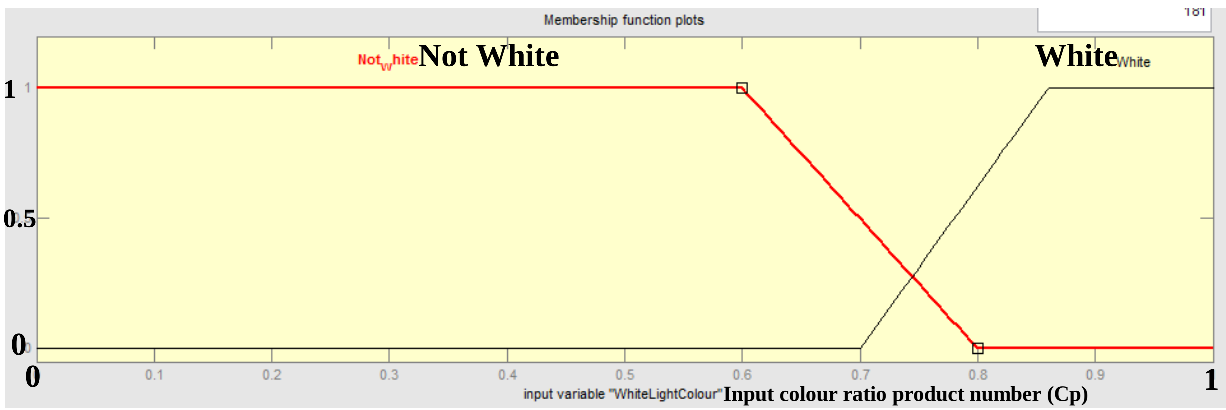


Figure 3.21: Screen shot of configured input Membership Function for Colour product signal

Figure 3.22 shows the controller output membership function algorithm plot for defuzzification of the output, P_r, for window shade position. The output position reference scale is 0 to 1, with 0 standing for fully closed and 1 for fully open window shade. Figure 3.23 is screenshot showing output membership function of the window shade position as was configured in the Fuzzy Logic toolbox.

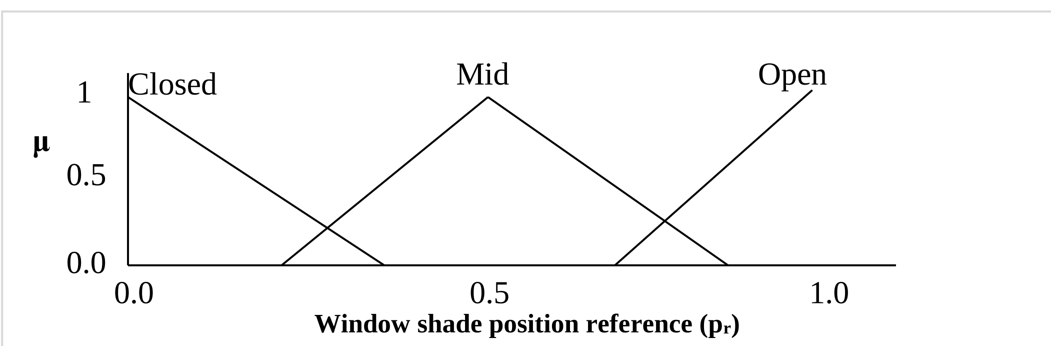


Figure 3.22: Window shade position output – Membership function algorithm plot

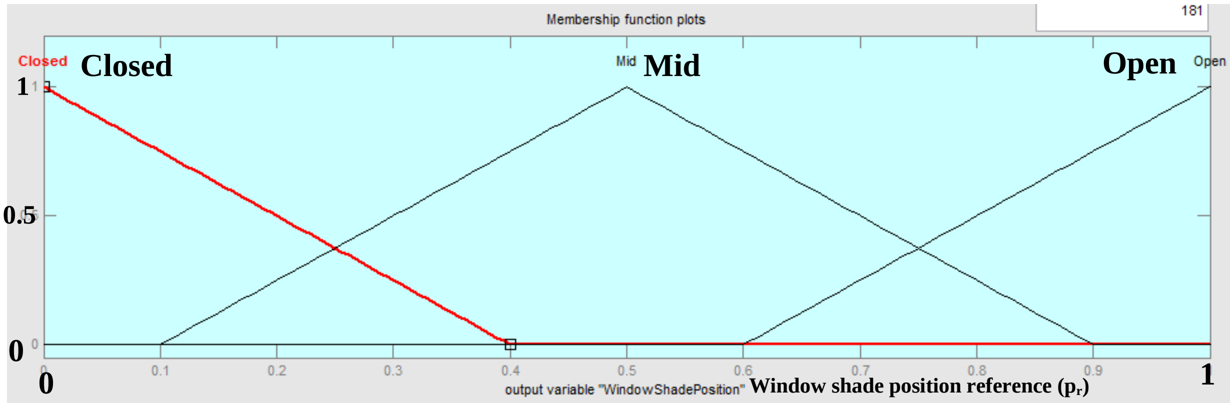


Figure 3.23: Screenshot of configured output Membership Function for window shade position

The operation of the fuzzy logic controller is based on a set of decision making control rules. The fuzzy logic rules for the window shade position controller consists of a collection of IF-THEN rules of the form

R^k: **IF** x_1 is F_1^k and x_2 is F_2^k **THEN** y is G_k (3-13)

For k =1, 2, 3… n.

Where:-

- R^k is the k^{th} rule;
- x_1, x_2 are members of U, for example, and y is member of V, and are the input and output of the fuzzy logic system, respectively;
- F_1^k, F_2^k and G_k are labels of fuzzy sets in U_1, U_2 and V representing the k^{th} antecedent pairs and consequent pair respectively;
- n is the number of rules.

Table 3.2 shows a matrix of rules (inference engine) for controlling the room's window shade position. The input, colour ratio product c_p, is the rows' side label, while input outdoor light level L_{od}, is the columns' top label. There are six rules for this particular fuzzy inference subsystem.

Figure 3.24 is screenshot of the rules used in the fuzzy logic controller, as configured in the Fuzzy logic toolbox.

Table 3.2: Control rules for input colour ratio product signal (c_p) and outdoor light level (l_{od}).

	IF Outdoor light (l_{od}) **IS**		
AND Colour product (c_p) **IS**	**Low**	**Mid**	**High**
White	THEN shade is Closed	THEN shade is Open	THEN shade is Mid open
Not White	THEN shade is Closed	THEN shade is Closed	THEN shade is Closed

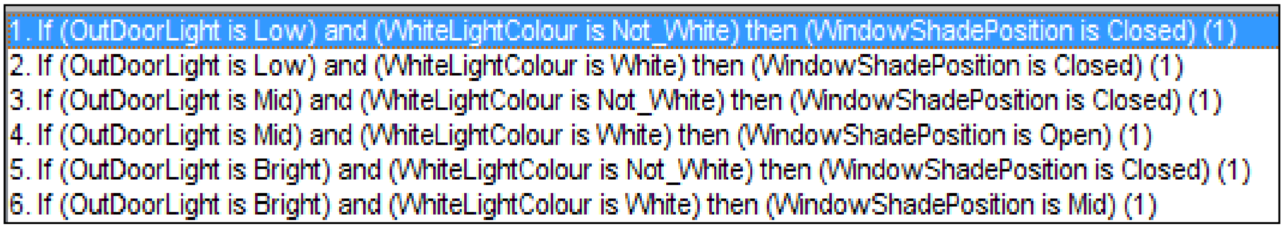

1. If (OutDoorLight is Low) and (WhiteLightColour is Not_White) then (WindowShadePosition is Closed) (1)
2. If (OutDoorLight is Low) and (WhiteLightColour is White) then (WindowShadePosition is Closed) (1)
3. If (OutDoorLight is Mid) and (WhiteLightColour is Not_White) then (WindowShadePosition is Closed) (1)
4. If (OutDoorLight is Mid) and (WhiteLightColour is White) then (WindowShadePosition is Open) (1)
5. If (OutDoorLight is Bright) and (WhiteLightColour is Not_White) then (WindowShadePosition is Closed) (1)
6. If (OutDoorLight is Bright) and (WhiteLightColour is White) then (WindowShadePosition is Mid) (1)

Figure 3.24: Screen shot of configured "IF –THEN" rules for the window shade position controller

3.8.3 LEDs' output light intensity Fuzzy Logic Controller – Functional block

This module consists of two interdependent inputs; the indoor light intensity level signal (L_k) and rate of change of the indoor light level (ΔL_k), which is extracted from the sensed indoor light level signal. Figure 3.25 is a representation of the fuzzy logic controller functional block for controlling the RGB LED output light intensity. The purpose of introducing the rate change of the light level in the room was to stabilize signal oscillations that would occur when control system tries to increase or decrease the room illumination levels.

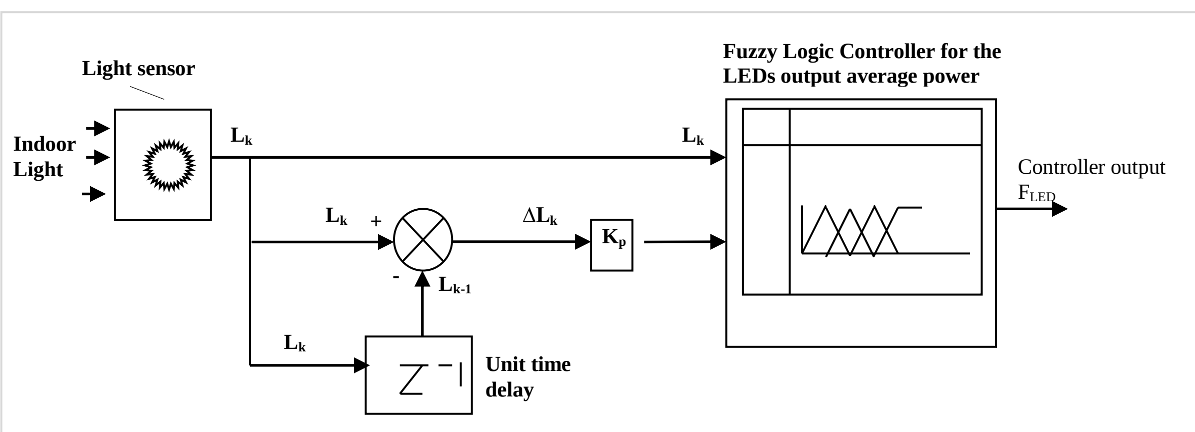


Figure 3.25: LEDs' output light intensity fuzzy logic controller – functional block

L_k is the indoor light level measured with a photometer at the k^{th} simulation sampling instant. ΔL_k is the rate of change of the indoor light level at the k^{th} sampling instant. k_p is a gain factor which determines the sensitivity of the controller to the changes in indoor light level/intensity. Z^{-1} indicates a unit time delay. Figure 3.26 is a screenshot showing the Simulink blocks that form the LEDs' fuzzy logic controller signal connections.

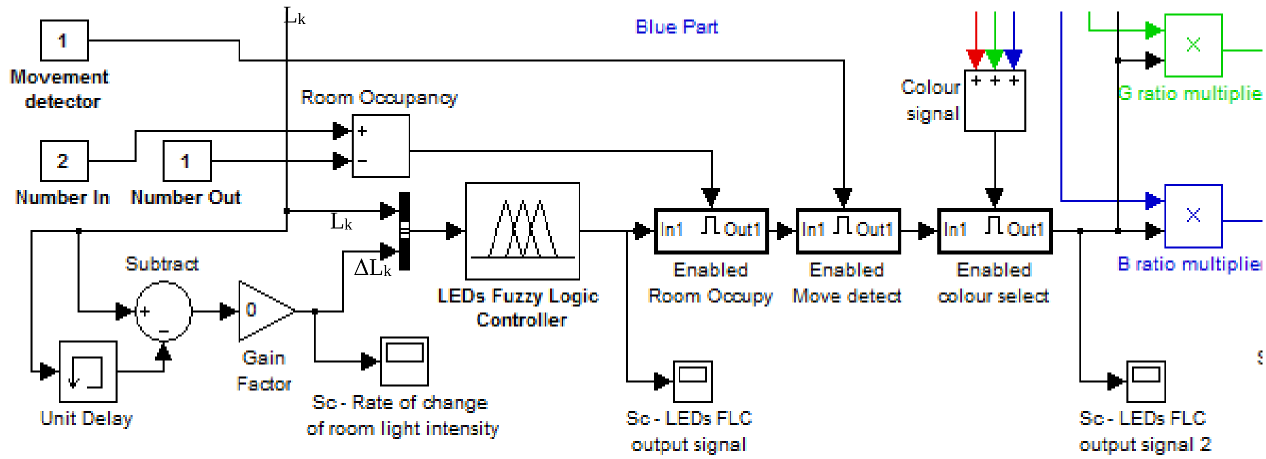


Figure 3.26: Screenshot showing section of assembled model for LEDs' fuzzy logic controller

The inputs to the LEDs' fuzzy logic controller are monitored using the indoor light intensity (room illumination level) feed-back scope, L_k, and rate of change of room light intensity scope, ΔL_k. The output of the fuzzy logic controller was monitored through two scopes: one immediately at the controller out by the scope block Sc-LEDs FLC output signal, and another after the room occupancy, movement detector, and the colour select enabler switches, Sc-LEDs FLC output signal 2.

Figure 3.27 is a screenshot of the fuzzy logic inference system for the LEDs output controller showing the two inputs and one output.

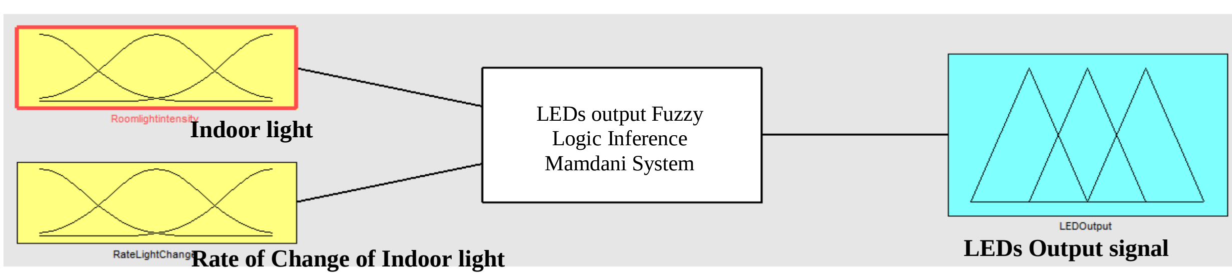


Figure 3.27: Screen shot of the configured fuzzy inference system for the LEDs' output controller

Figure 3.28 is the membership function algorithm plot for the room light intensity level where the universe of discourse ranges from 0 to 10. Figure 3.29 is screenshot of the configured indoor light intensity membership function.

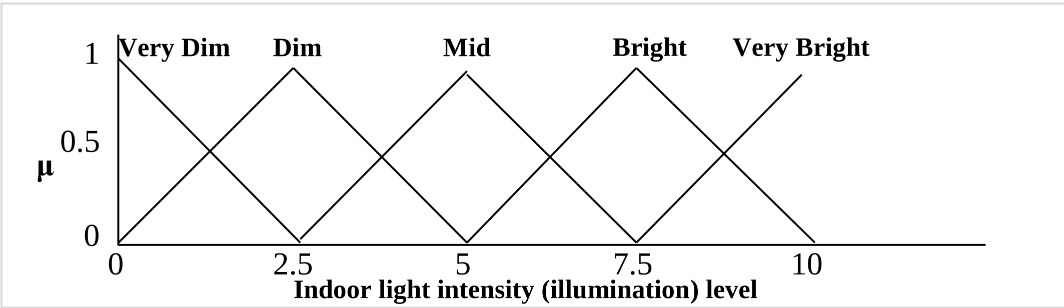


Figure 3.28: Indoor light intensity – input membership function algorithm plot

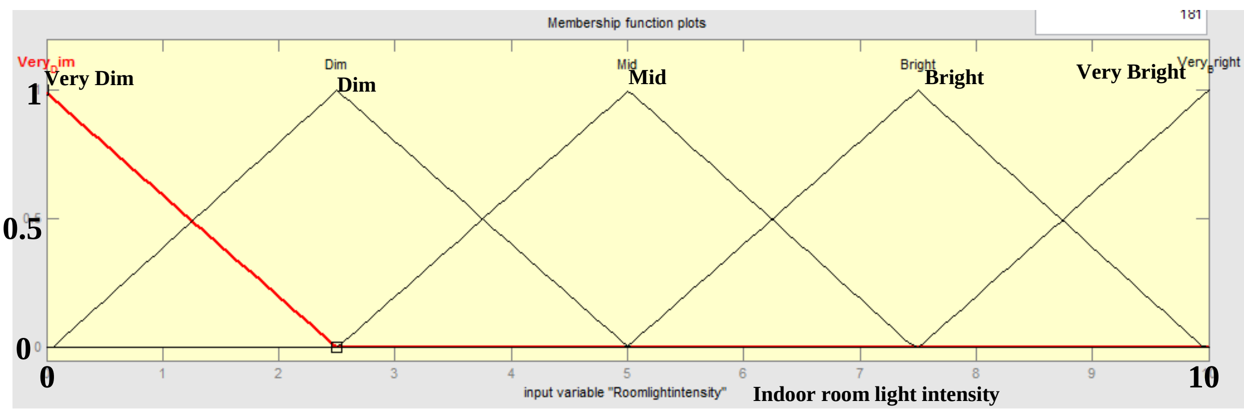


Figure 3.29: Screenshot of configured input Membership Function for indoor light intensity.

Figure 3.30 is the membership function algorithm plot for the rate of change of the indoor light intensity. The universe of discourse ranges from -1 to 1. The configured membership function is shown by screenshot in figure 3.31.

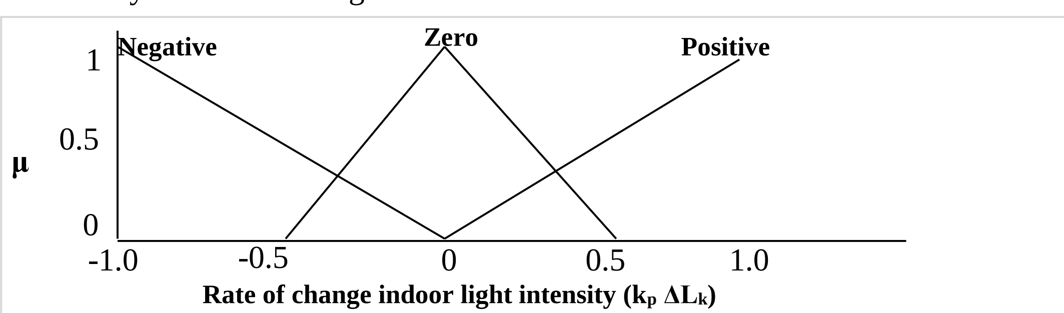


Figure 3.30: Rate of change of Indoor light intensity – membership function algorithm plot

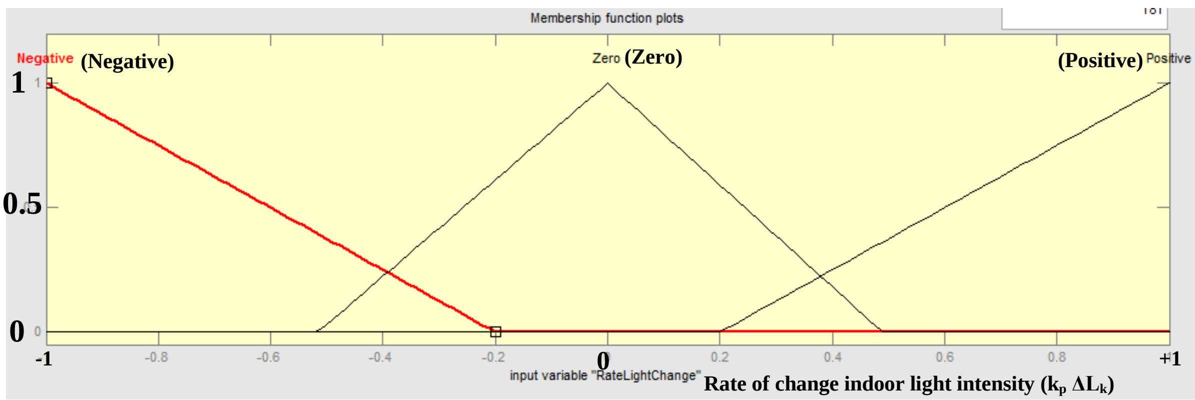


Figure 3.31: Screenshot of configured input Membership Function for rate of change of indoor light

Figure 3.32 is the membership function algorithm plot for output of the LEDs' fuzzy logic controller. The universe of discourse range was from 0 to 2. This range was set for convenience of allowing multiplication of the respective colour ratios, the convert the product output to a range of -1 to +1. The available simulink PWM generator allowed input of -1 to +1 hence the LEDs' controller output was subtracted a 1 constant value, after colour ratio multiplication.

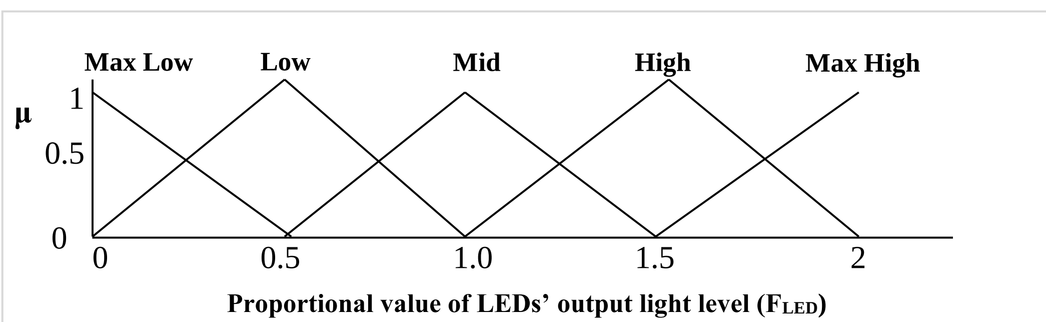


Figure 3.32: LEDs' output light intensity – output membership function algorithm

Figure 3.33 is the screenshot showing the configured output membership function in the MATLAB-Fuzzy logic Toolbox.

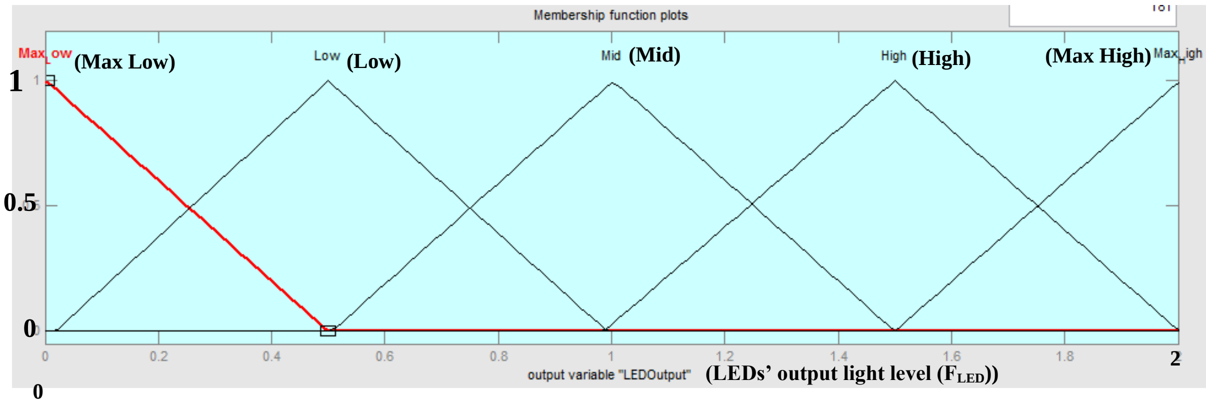


Figure 3.33: Screen shot of configured output Membership Function for LEDs' light level

Table 3.3 shows a matrix of rules for controlling the LEDs average power output using the indoor light level L_k and its rate of change $\Delta \mathbf{L_k}$. The input, light level L_k, is the rows' side label while input light level rate of change $\Delta \mathbf{L_k}$, is the columns' top labels. There are 15 rules for this fuzzy inference subsystem. The fuzzy rule in the table 3.3 consists of a collection of fuzzy IF-THEN rules of the form:

R^x: IF L_k is $F_{Lk}{}^x$ and $\Delta \mathbf{L_k}$ is $F_{\Delta \mathbf{Lk}}{}^x$ THEN LEDs' output light level is G_x. (3-14)

for x =1, 2, 3… n.

Where R^x is the x^{th} fuzzy rule, and n is the number of rules. $F_{Lk}{}^x$ is the indoor light level fuzzy set, and $F_{\Delta \mathbf{Lk}}{}^x$ is the indoor light level rate of change fuzzy set for the x^{th} fuzzy rule. G_x is the expected LEDs' output light level for the x^{th} fuzzy rule. Figure 3.34 is screen shot of the configured fuzzy rules.

Table 3.3: Indoor lighting LEDs average power output control rules (decision making table)

	AND Rate of change (ΔL_k) **IS**		
IF Room light (L_k) **IS**	**Negative**	**Zero**	**Positive**
Very Dim	THEN LED output is **Max High**	THEN LED output is **Max High**	THEN LED output is **High**
Dim	THEN LED output is **Max High**	THEN LED output is **High**	THEN LED output is **Mid**
Mid	THEN LED output is **High**	THEN LED output is **Mid**	THEN LED output is **Low**
Bright	THEN LED output is **Mid**	THEN LED output is **Low**	THEN LED output is **Max Low**
Very Bright	THEN LED output is **Low**	THEN LED output is **Max Low**	THEN LED output is **Max Low**

1. If (Roomlightintensity is Very_Dim) and (RateLightChange is Negative) then (LEDOutput is Max_High) (1)
2. If (Roomlightintensity is Very_Dim) and (RateLightChange is Zero) then (LEDOutput is Max_High) (1)
3. If (Roomlightintensity is Very_Dim) and (RateLightChange is Positive) then (LEDOutput is High) (1)
4. If (Roomlightintensity is Dim) and (RateLightChange is Negative) then (LEDOutput is Max_High) (1)
5. If (Roomlightintensity is Dim) and (RateLightChange is Zero) then (LEDOutput is High) (1)
6. If (Roomlightintensity is Dim) and (RateLightChange is Positive) then (LEDOutput is Mid) (1)
7. If (Roomlightintensity is Mid) and (RateLightChange is Negative) then (LEDOutput is High) (1)
8. If (Roomlightintensity is Mid) and (RateLightChange is Zero) then (LEDOutput is Mid) (1)
9. If (Roomlightintensity is Mid) and (RateLightChange is Positive) then (LEDOutput is Low) (1)
10. If (Roomlightintensity is Bright) and (RateLightChange is Negative) then (LEDOutput is Mid) (1)
11. If (Roomlightintensity is Bright) and (RateLightChange is Zero) then (LEDOutput is Low) (1)
12. If (Roomlightintensity is Bright) and (RateLightChange is Positive) then (LEDOutput is Max_Low) (1)
13. If (Roomlightintensity is Very_Bright) and (RateLightChange is Negative) then (LEDOutput is Low) (1)
14. If (Roomlightintensity is Very_Bright) and (RateLightChange is Zero) then (LEDOutput is Max_Low) (1)
15. If (Roomlightintensity is Very_Bright) and (RateLightChange is Positive) then (LEDOutput is Max_Low) (1)

Figure 3.34: Screenshot of the configured "IF-THEN" fuzzy rules for the LEDs' output controller

3.8.4 Room Occupancy, Movement detector and Colour Decoder Signals – Enabler Switches

The following three signals were configured to allow or stop the LEDs fuzzy controller output signal:

- Room occupancy signal
- Movement detector signal
- Colour signal

Each of the signals was assigned an enabler switch. The enabler switches were connected in series, as shown by the screenshot in figure 3.35. Each enabler switch would allow passage of the LEDs' fuzzy logic controller output signal only when the switch control signal value is 0.6 and above.

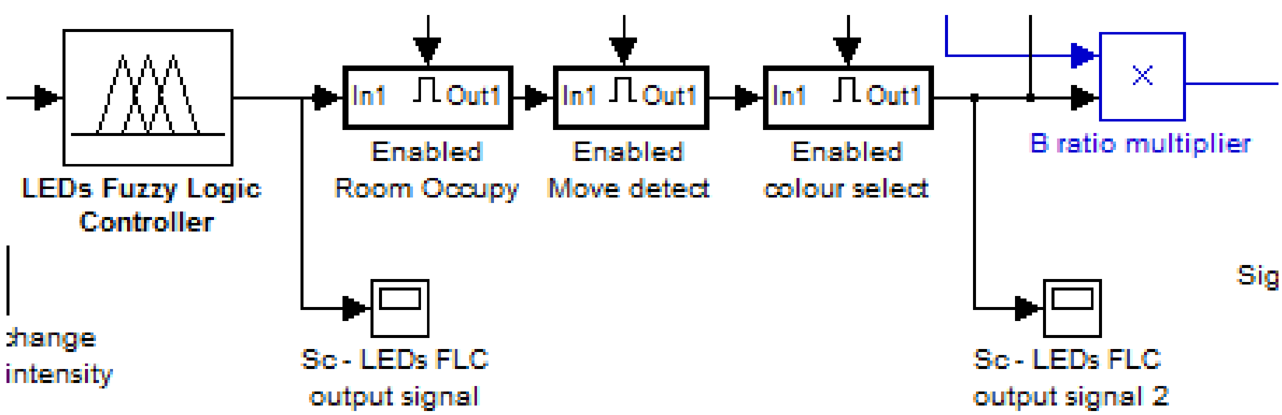


Figure 3.35: Screenshot of a section of the assembled model showing enabler switches.

As shown by screenshot in figure 3.36, a fraction (ratio) value for each colour is first calculated and the ratio value used is to determine if the LEDs' output light would be white or not; if their product output is 0.85 to 1, then the LEDs light colour is fully white. The sum of the colour ratios was used for the colour signal enabler switch. The screen shot in figure 3.37 show that the colour fractions (ratios) are used individually as a multiplier of the LEDs' fuzzy controller output signal and determine the respective LED's PWM generation output duty cycle and hence the LED luminance level.

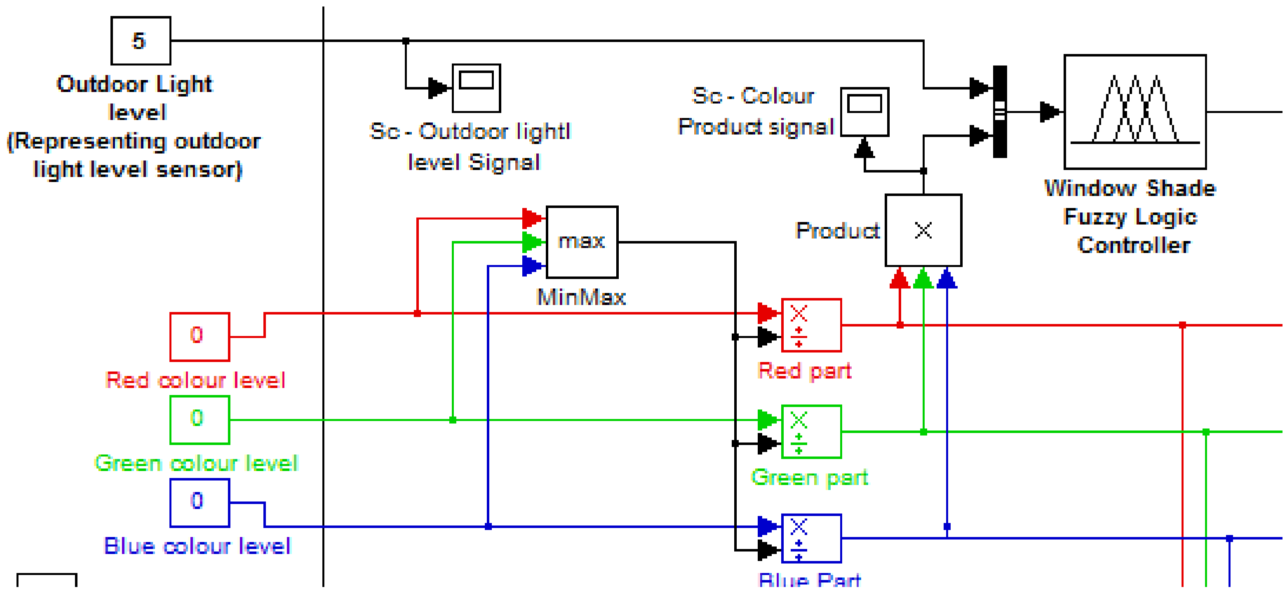


Figure 3.36: Screenshot of a section of assembled model showing colour ratio calculations

The selected SIMULINK PWM generator required an input signal which ranges from -1 to +1. But a signal with negative value, from the fuzzy logic controller, could not be multiplied with a fraction number representing the colour intensity. To avoid this, the LEDs fuzzy logic controller output signal level was set to range from 0 to 2. This signal range would be converted to the required -1 to +1 range by introducing a value of -1 to the final signal.

The controller's output signal is first multiplied by each colour portion, at their respective connection points, then a constant value of 1 is subtracted (signal off-set) from product signal of the multiplication. This process is illustrated in screenshot of the control signal blocks in figure 3.37.

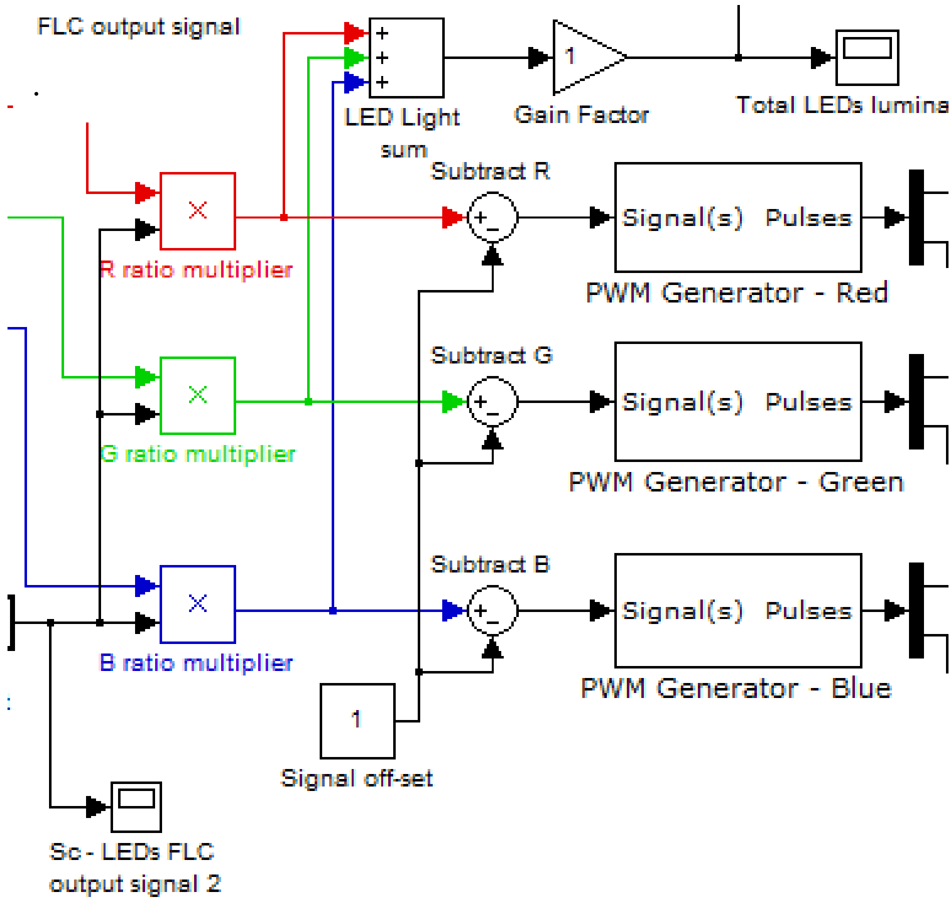


Figure 3.37: Screenshot of section of assembled model showing the respective colour ratio signals

Each signal for the respective PWM generator represents the ratio composition of the corresponding colour.

3.8.5 LEDs' Driver – Controller Functional Block

The LEDs' driver is represented by a signal controlled switch for each respective colour, as shown by the screenshot section in figure 3.38. The switch in each LED circuit opens and closes in rhythm with the pulses from the respective colour PWM generator. The resistor in each LED circuit limits the peak current.

Also shown in the figure 3.38 is the indoor light intensity (room illumination level) feedback circuit. The room illumination level feedback signal, which stands in for the indoor light sensor, is a sum of the outdoor light and the LEDs' output light.

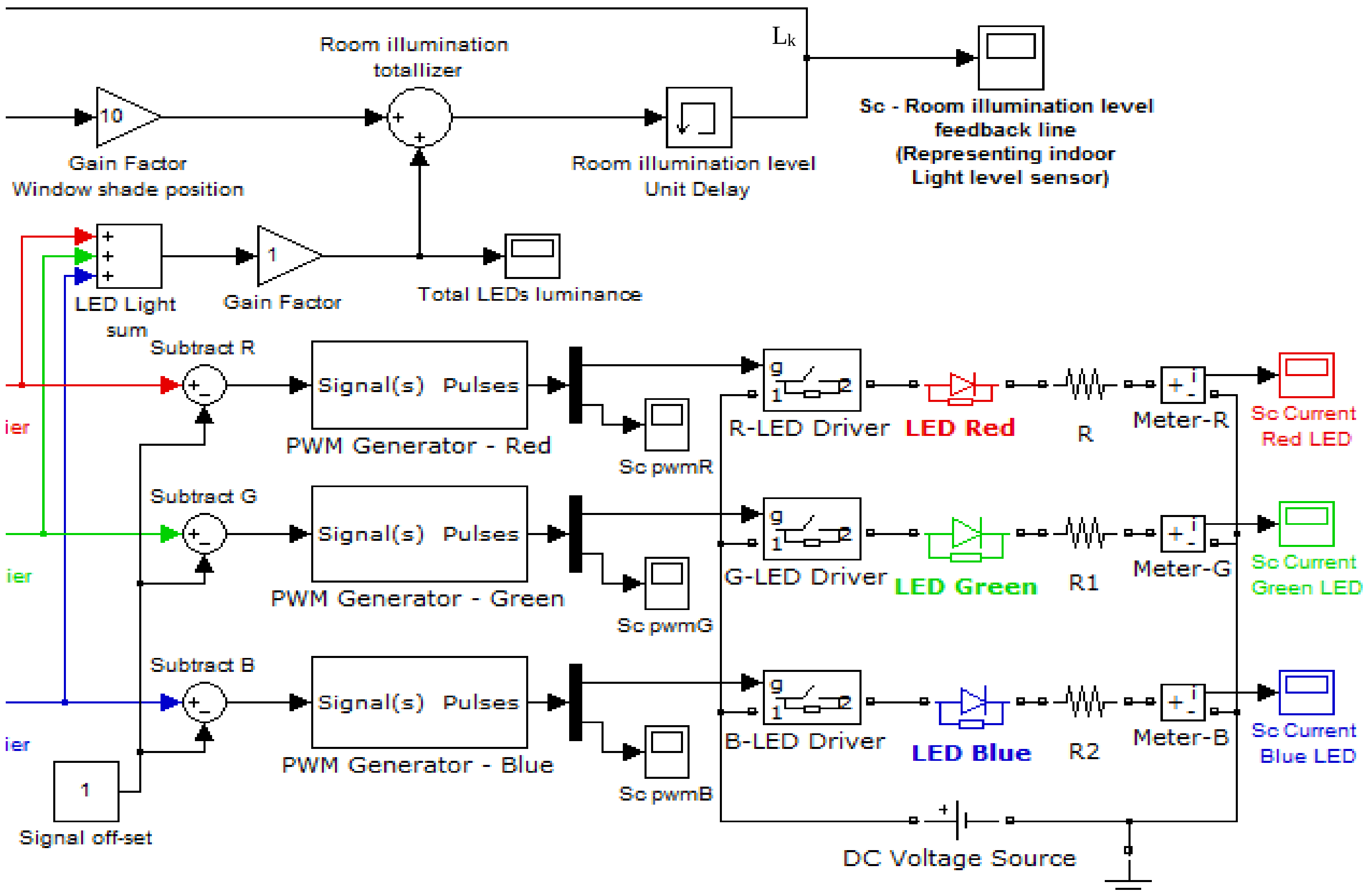


Figure 3.38: Screenshot of section of assembled model showing LEDs' driver and the indoor light intensity level (L_k) feedback line

CHAPTER 4 - RESULTS AND DISCUSSIONS

4.1 Introduction

The purpose of this chapter is to simulate and confirm whether the model and control algorithms based on the fuzzy logic can be used to meet the objectives and answer the research questions set out in chapter 1 sections1.3 and 1.4.

Inputs to the model were in form of constant values based on Simulink constant-blocks that are specific for outdoor light intensity, red colour, green colour, blue colour, movement detector, number entering room, and number leaving room respectively. A sinusoidal signal generator was also used as input for the outdoor light sensor.

Throughout the experiment, the simulation duration was set at 0.005 seconds.

Outputs of the model were monitored by means of Simulink scope-blocks. For each specific input value and simulation time, the corresponding model signal level was monitored for the window shade position fuzzy logic controller output, the summed up indoor light intensity (indoor light intensity feedback), the rate of change of the indoor light intensity, the LEDs fuzzy logic controller output, the light colour ratio product, and the LEDs' currents.

Effects of various gain factor values for the rate of change of indoor light intensity signal, the window shade position fuzzy logic controller output signal, and the LEDs control sum-signal were checked and the optimum performing values fixed for the model investigation tests.

The following investigation tests were carried out:

1. Effect of gain factor values for rate of change of indoor light intensity on stability of the indoor (room) illumination levels.
2. Effect of gain factor values for the window shade position fuzzy logic controller output on indoor illumination levels.
3. Effect of outdoor light intensity on indoor illumination levels and the LEDs' output.
4. Effect of different values of the Red, Green and Blue colour portions on indoor illumination levels and the respective LED's current pulse width.

5. Effect of zero value for the colour decoder, the movement detector, and room occupancy signals on indoor illumination levels and the LEDs' fuzzy logic controller output signal.
6. Effect of too high and negative values of outdoor light intensity signal on window shade controller output signal, indoor illumination levels, and the LEDs' fuzzy logic controller output signal.
7. Effect of changing the shape of the fuzzy logic controllers' membership function plots.
8. Effect of shifting the mid membership function of the Fuzzy Logic controllers from the middle position to the right hand-side of the plot.

Each simulation test outputs were displayed on computer screen. Screenshots were taken and the display waveforms pasted on table-forms for comparison purposes. For some investigations, simulation model signal output values were tabulated and the results displayed in form of line graphs.

4.2 Effect of gain factor value for Rate of Change of the Indoor Light Intensity.

The objective of this test was to check how values of rate of change of the indoor light intensity (ΔL_k) affect the oscillations of the indoor light intensity (L_k) and which value has the best system stability. This refers to figure 3.26, in chapter 3, for the model's LEDs light output fuzzy logic controller. Based on the LEDs output fuzzy logic controller input membership functions (figures 3.29 and 3.31), and control rules (table 3.3), the lighting system was expected to be most stable at gain factor value of 1.

4.2.1 Results on testing effect of gain factor value for rate of change of the indoor light intensity on stability of the lighting system simulation model

In this investigation test, constant values of the outdoor light signal, equal values for the colour portions, and enabling signals for the room movement detector and the room occupancy are maintained. The simulation model input data had constant values as shown in table 4.1. Graph set 4.1 compares the screenshot waveforms and their settlement values for indoor illumination level feedback signal, rate of change of indoor illumination levels, and output of the LED light intensity fuzzy logic controller at various values of gain factor for the rate of change of indoor illumination levels.

Table 4.1: Constant values – Effect of Gain factor (k_p) for Rate of change of indoor light levels

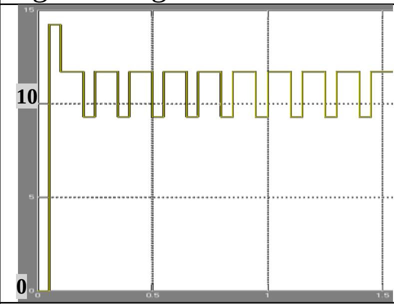
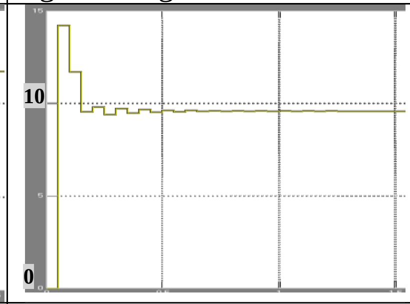
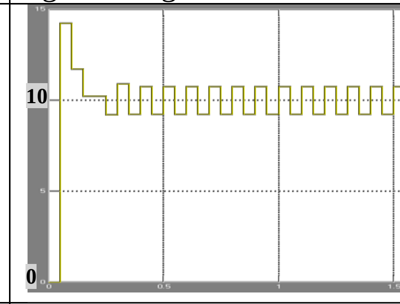
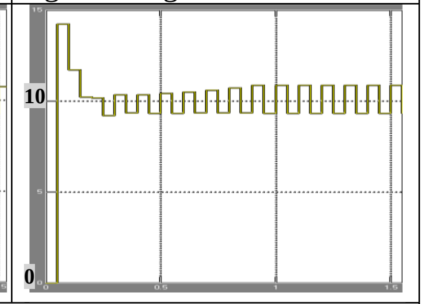
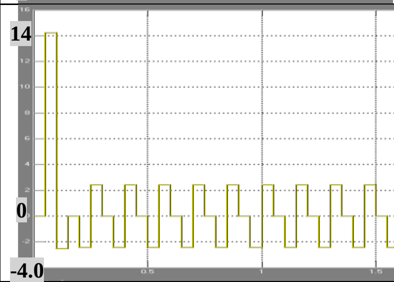
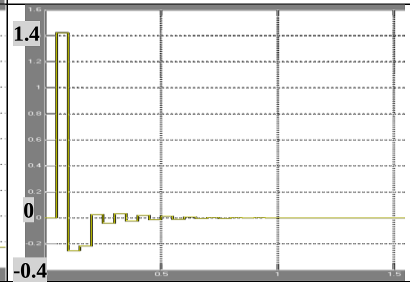
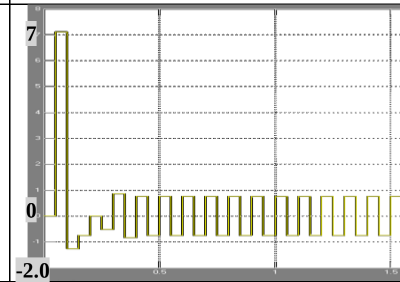
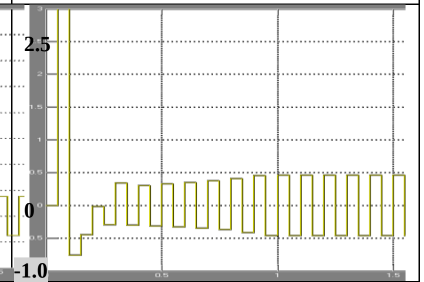
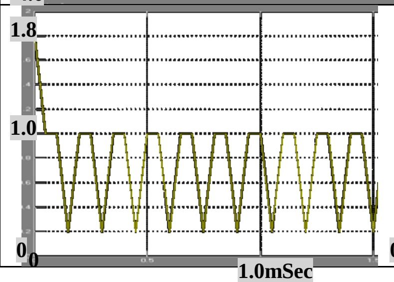
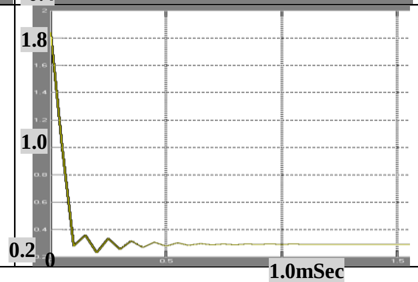
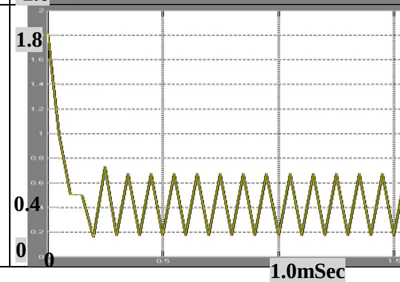
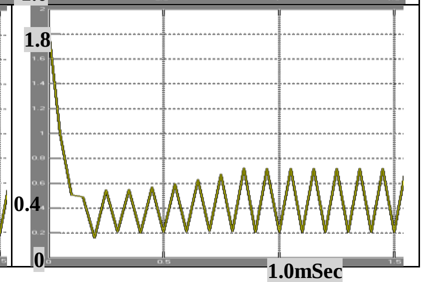
Outdoor light level	Red colour part value	Green colour part value	Blue colour part value	Movement detector value	Number entering room	Number leaving room	Window shade position gain	LED light control sum gain
5	1	1	1	1	2	1	10	1

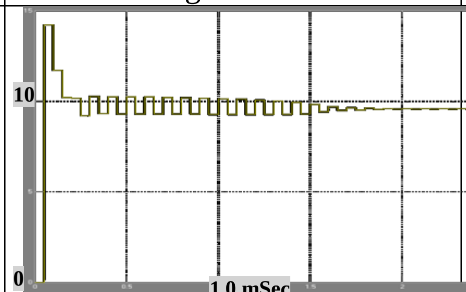
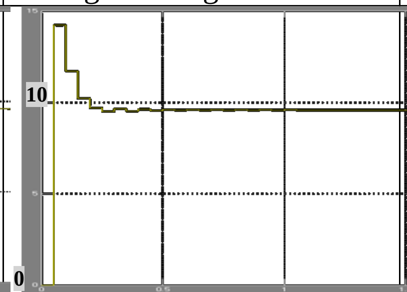
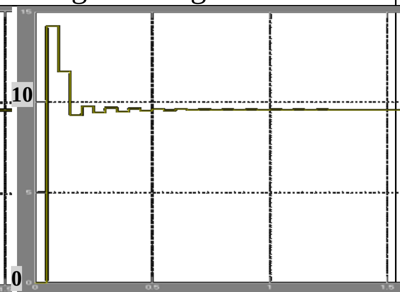
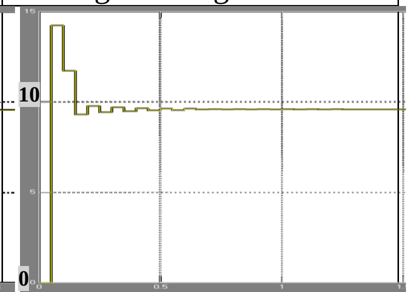
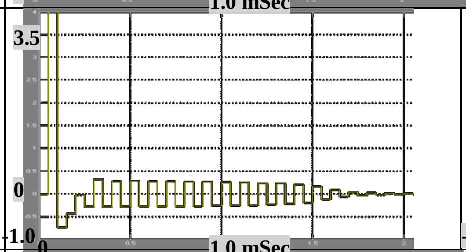
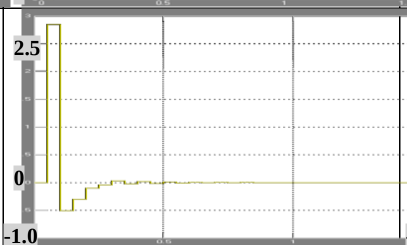
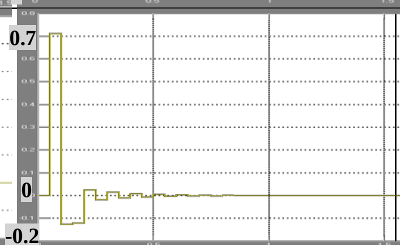
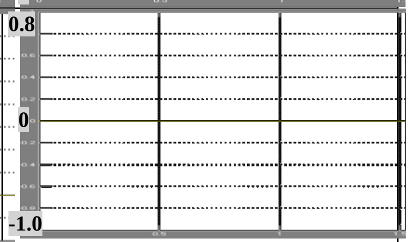
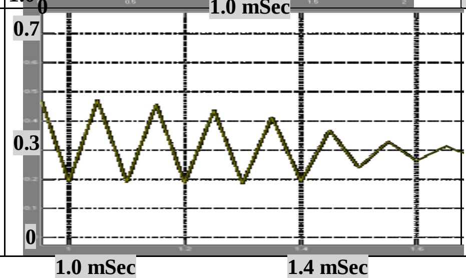
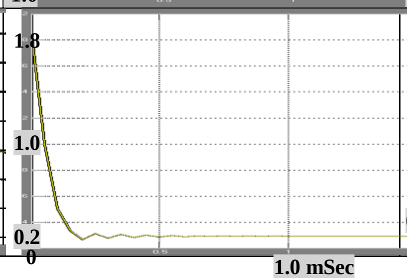
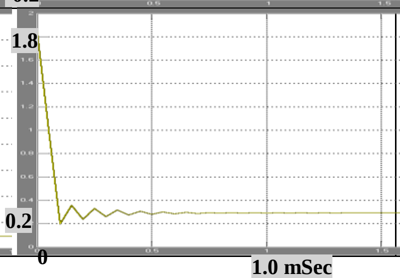
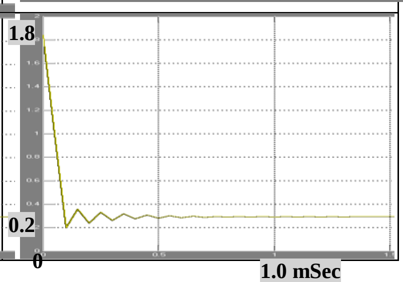
The results were obtained from the time based graphical representation of the simulation on three scopes of the MATLAB Simulink simulation model. The results are presented by screenshots and displayed in table format for comparison purposes as shown in graphs 4.1.

At gain factor values of 10, 0.5, and 0.3 the lighting system does not settle. But at gain value of 1, 0.292, 0.2, 0.05 and 0 the lighting system settles down; about 9 for the indoor illumination level value, about 0.3 for the LEDs' fuzzy logic controller output signal and 0.0 (zero) for the rate of change of indoor light intensity. However, the system settles fastest at gain value of 0.2.

The waveforms in graph sets 4.1 show that the gain factor value on output of the rate of change of the indoor light intensity affects the stability of the lighting control system.

Graph set 4.1: Set of screenshots of respective scopes - Effect of Gain factor (k_p) for Rate of change of indoor light level – Comparing graphical shapes and values

	Rate of change of indoor light level gain at 10	Rate of change of indoor light level gain at 1	Rate of change of indoor light level gain at 0.5	Rate of change of indoor light level gain at 0.3
Indoor light level feedback signal				
Rate of change of indoor illumination levels				
Output of the LED light intensity fuzzy logic controller				

	Rate of change of indoor light level gain at 0.292	Rate of change of indoor light level gain at 0.2	Rate of change of indoor light level gain at 0.05	Rate of change of indoor light level gain at 0
Indoor light level feedback signal				
Rate of change of indoor illumination levels				
Output of the LED light intensity fuzzy logic controller				

4.2.2 Discussion on effect of gain factor value for rate of change of indoor light intensity on stability of the lighting system

The investigation test results show that the system stability does not depend on magnitude of the rate of change signal but on some critical values of the rate of change. The system is seen to be stable even without input from the rate of change of the indoor illumination levels.

The system was expected to be most stable at gain value of 1, which the simulation results show not be so another value, 0.2, which is almost zero.

The simulation results show that the lighting system is even more stable without the rate of change of the indoor light intensity.

4.3 Effect of Window Shade Position Fuzzy Logic Controller Output Gain factor

The objective of this test was to check how the values for the model's window shade position controller output signal gain factor affect the overall indoor light intensity (L_k) and which gain factor value is most suitable and realistic for the model. This refers to figure 3.38, section of the assembled model showing LEDs' driver and the indoor light intensity level (L_k) feedback line.

Based on the window shade position fuzzy logic controller input membership functions (figures 3.19 and 3.21), the output membership function (figure 3.23), and control rules (table 3.1), the model window shade opening was expected to range from 0 to 10 at a gain factor value of 10. Gain factor values above 10 would make the indoor illumination level (L_k) for input to the LED's fuzzy controller to be outside the range, as per the membership function in figure 3.29. Gain values of more than 10 were expected to make the LEDs controller output signal insensitive to the input.

It was also expected that at window shade gain factor value of zero, the indoor illumination level (L_k) would be composed of the LEDs signal only, and the L_k signal value would be 6 (which is 3 times the set maximum LEDs fuzzy logic controller output signal value of 2 as per the model section shown in figure 3.37 the LEDs light sum).

4.3.1 Results on testing effect of the window shade fuzzy logic controller output gain factor on indoor illumination level feedback signal and the LEDs' output

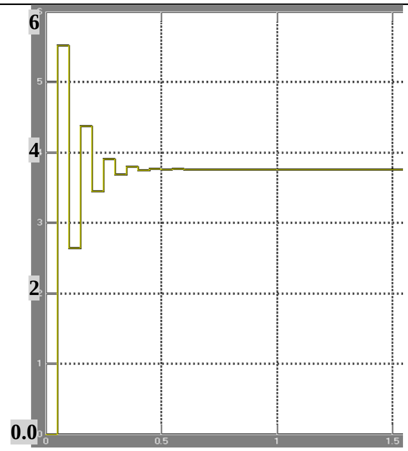
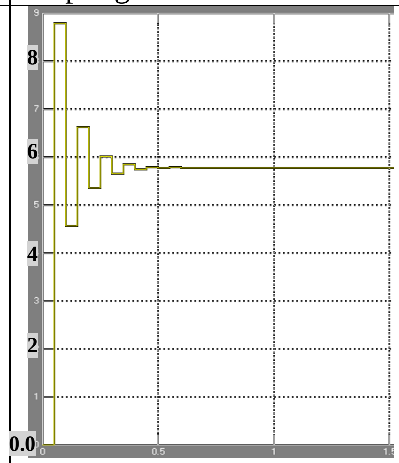
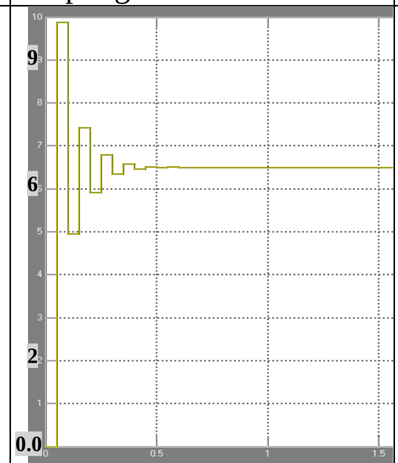
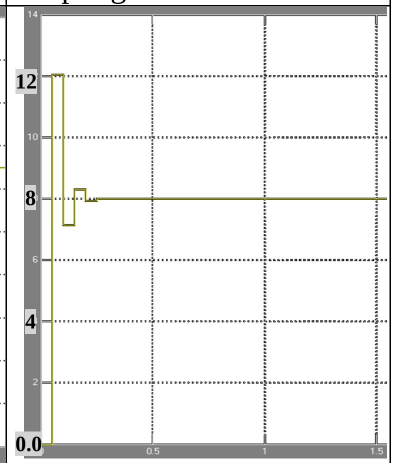
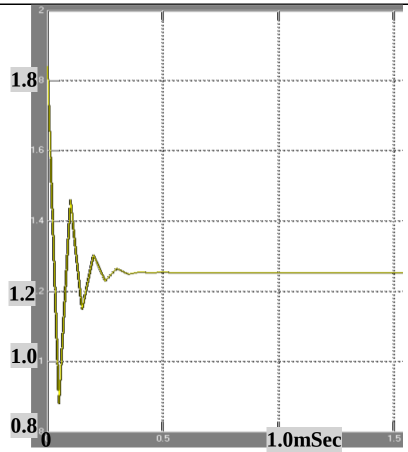
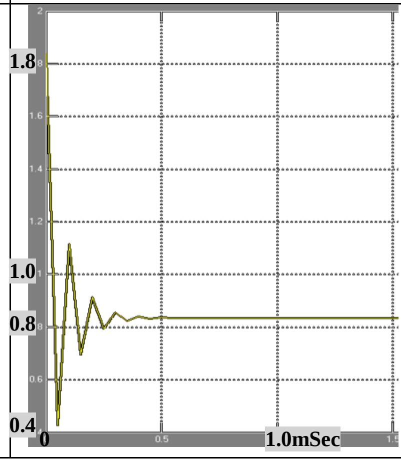
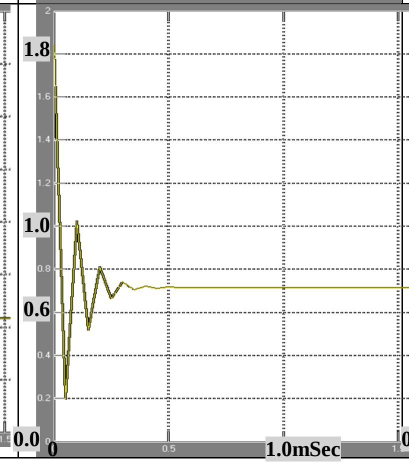
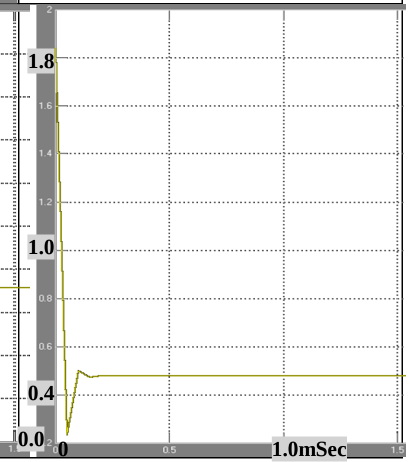
In this investigation test, constant values of the outdoor light signal, equal values for the colour portions, and enabling signals for the room movement detector and the room occupancy were maintained. The simulation model input data had zero value for the rate of change of the indoor light intensity as shown in table 4.2. Graph set 4.2 compares the shapes and values of measured indoor illumination level feedback signal, and output of the LEDs fuzzy logic controller for various values of gain factor on the output of the window shade position fuzzy logic controller.

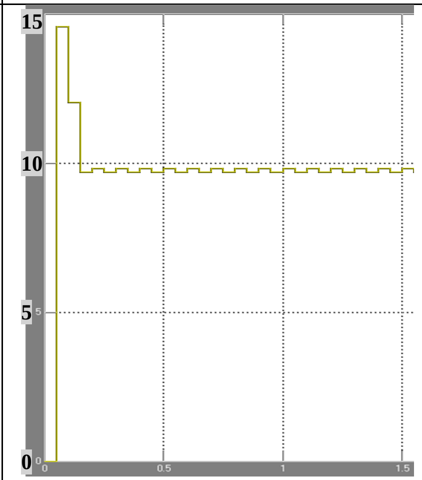
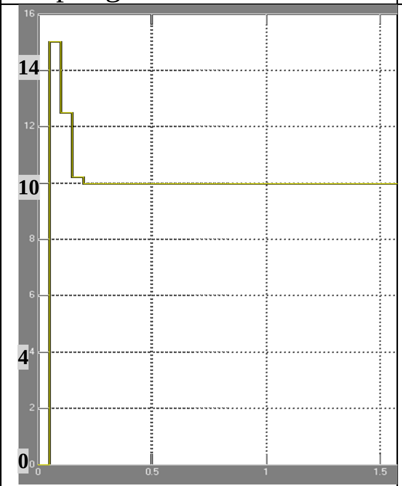
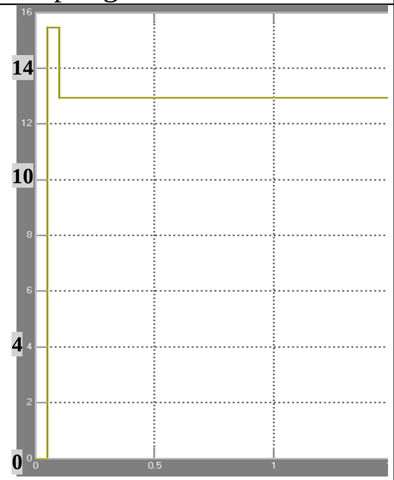
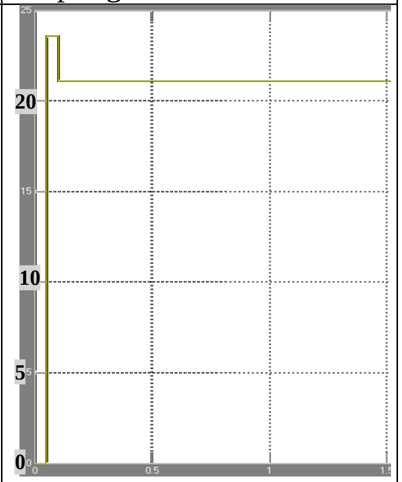
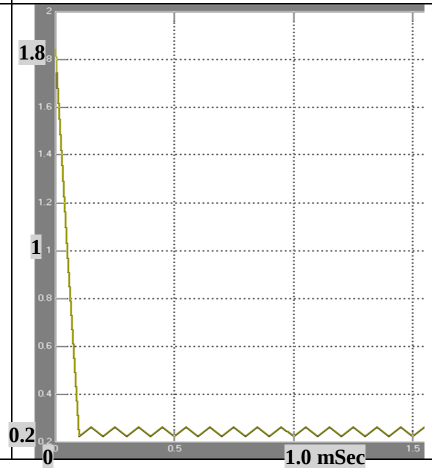
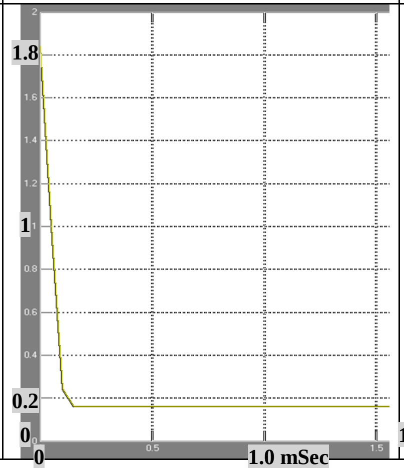
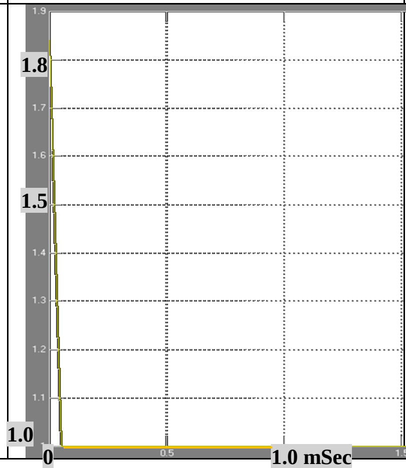
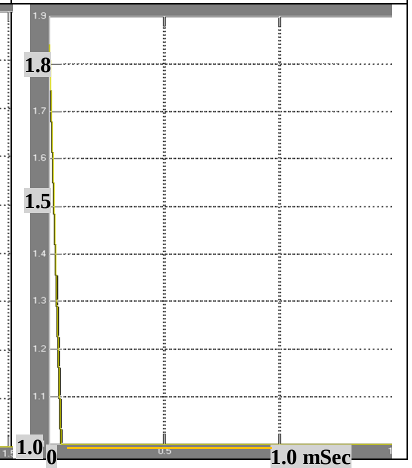
Table 4.2: Constant values – Effect of gain factor (k_w) for window shade position controller output.

Outdoor light level value	Red colour part value	Green colour part value	Blue colour part value	Movement detector value	Number entering room	Number leaving room	Rate of change of indoor light intensity gain value	LED light control sum gain value
5	1	1	1	1	2	1	0	1

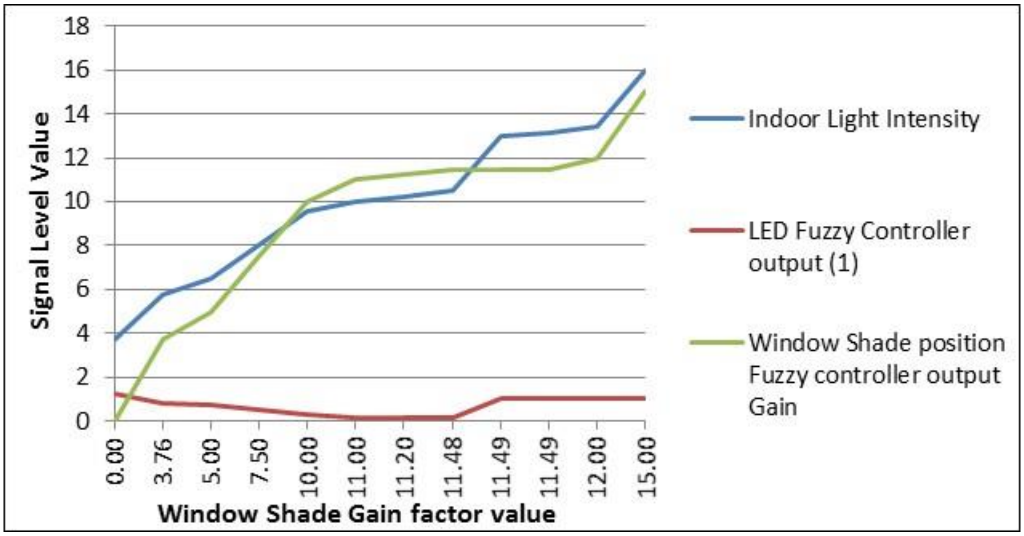
The results were obtained from the time based graphical representation of the simulation on three scopes of the MATLAB Simulink simulation model. The results are presented by screenshots displayed in table format for column-wise comparison purposes. The results are also shown in line graph 4.3, where the y-axis represents values of the indoor light intensity, the LEDs fuzzy logic controller output, and the window shade position fuzzy logic controller output gain factor. The x-axis of the line graph represents the gain factor value for the window shade position fuzzy logic controller output.

Graph set 4.2: Set of screen shots of respective scopes – Effects of gain factor (k_w) for window shade controller output.

	Window Shade Position Fuzzy logic controller output gain factor of 0	Window Shade Position Fuzzy logic controller output gain factor of 3.76	Window Shade Position Fuzzy logic controller output gain factor of 5	Window Shade Position Fuzzy logic controller output gain factor of 7.5
Indoor light level feedback signal				
Output of the LED light intensity fuzzy logic controller				

	Window Shade Position Fuzzy logic controller output gain at 10	Window Shade Position Fuzzy logic controller output gain at 10.5	Window Shade Position Fuzzy logic controller output gain at 11	Window Shade Position Fuzzy logic controller output gain at 20
Indoor light level feedback signal				
Output of the LED light intensity fuzzy logic controller				

Graph 4.3 is line graph showing the relationship between the window shade position fuzzy logic controller output gain factor value and the indoor light intensity values, and the LEDs fuzzy logic controller output values.



Graph 4.3: Line graph – effect of the window shade controller output gain factor.

From graph set 4.2, the shapes of the plots for each monitoring point are similar for each window shade controller output gain factor. It was also noted that the indoor illumination level values increase with increase of the window shade controller output gain factor. At gain factor value of 0, the indoor illumination level value first shoots up to a value of about 5.5 then settles down to 3.7, the lowest stable value, while the LEDs fuzzy logic controller output shoots up to about 1.8 then settles to a value of about 1.26, which is the highest stable value. At window shade gain factor value of 10, the indoor illumination level value is about 9.5, with some noticeable oscillations, while the LEDs fuzzy logic controller output was oscillating at about 0.25. At window shade gain factor value of 10.5, the indoor illumination level value is about 10, while the LEDs fuzzy logic controller output value was about 0.16, the lowest attained value. At window shade gain factor value of 11.5, the indoor illumination level value is about 13, while the LEDs fuzzy logic controller output value was 1, a value which was not changing even with other higher values of the window shade gain factors.

The line graph in graph 4.3, also shows that the indoor illumination level values increases with increase of the window shade gain factor, but the LEDs' controller output value decreases to lowest level of about 0.16, then rises to value of 1 for all indoor light intensity values beyond 10.5 and window shade gain factor values above 11.49.

4.3.2 Discussion on effect of the room's window shade position fuzzy logic controller output gain factor

All the objectives for this investigation test were fully met. The most appropriate window shade position fuzzy logic controller output gain factor value was confirmed to be 10. The window shade fuzzy logic controller, which is of approximation type, output range from 0.1 to 0.9 instead of 0 to 10 for exact conventional controllers. For the closed window shade, the contribution to the indoor light intensity (L_k) was about 1 instead of zero value. And the maximum outdoor light contribution for the L_k was about 9 instead of the exact value of 10 for the fully open window shade position.

At window shade gain factor value of 0, window's outdoor light contribution to L_k was also 0. The LEDs' contribution to L_k, which was expected to have maximum value of 6, was noted to be lower at about 5.5 at the first oscillation peak value. As per the LEDs fuzzy logic control rules in table 3.3, an input value of 5.5 would be in the membership function set of "mid", and the expected controller's output signal value would be in set of "high" whose output signal value is about 1.5. This LEDs fuzzy logic controller output (1.5x3 representing the L_k) would be computed to the settled L_k value of 3.7 and LEDs Fuzzy logic controller output value of 1.3. This means the required room illumination level is achieved when LEDs fuzzy logic controller output signal is at the membership function set of "mid" level.

This investigation tests confirmed that window shade gain factor values above 10 affects sensitivity of the LEDs' fuzzy logic controller. For all indoor (room) light intensity (L_k) with values above 10.5, the LEDs fuzzy logic controller output signal would be faulty and cannot be relied on because it remains invariable at value level of 1.

4.4 Effect of Outdoor Light Intensity Levels

The objective of this test was to check how various values of the outdoor light intensity affect the model's window shade position fuzzy logic controller output signal, the overall room illumination levels (indoor light intensity L_k), and the LEDs fuzzy logic controller output signals. This was in reference to the system model design shown in figure 3.14 and the respective fuzzy logic controller membership functions in chapter 3.

In this test, the outputs of the window shade position fuzzy logic controller were expected to follow the “if-then” control rules in table 3.1. The outdoor light intensity values were varied from 0 to 10. The window shade position fuzzy controller output values were expected to range from 0 to 0.3 for closed window shade position, from 0.8 to 1 for fully open window shade position, and from 0.4 to 0.7 for mid open window shade position.

4.4.1 Results of testing effect of outdoor light intensity level on indoor illumination levels and the LEDs’ output.

The test was carried out at constant value of the window shade fuzzy logic controller output gain factor, zero value for rate of change of the indoor light intensity, equal level values of the colour portions, enabled room movement detector, and enabled room occupancy. The simulation model data points were of values as shown in table 4.3. Graph set 4.4 compares the shapes and values of measured indoor illumination level feedback signal, and output of the LED light intensity fuzzy logic controller for various values of the outdoor light intensity signal. The test results are also shown in line graph 4.5, where the values of the outdoor light intensity are compared with the resulting values of the window shade position fuzzy logic controller output, the indoor illumination levels, and the LEDs’ fuzzy logic controller output.

A signal generator with sinusoidal output was also used as the outdoor light intensity signal. The outdoor light intensity signal wave form and the resulting wave forms of the window shade controller output, the indoor illumination level, and the LEDs’ controller output signals are tabulated in graph set 4.6.

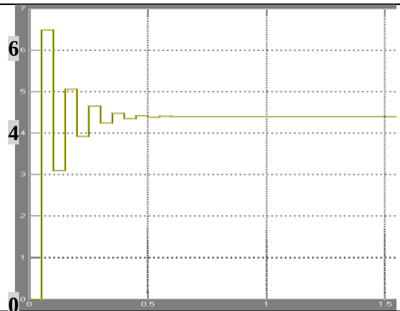
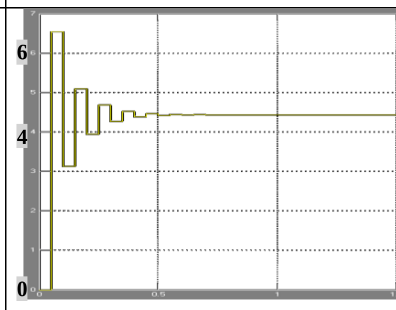
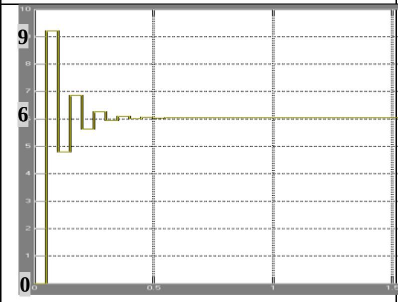
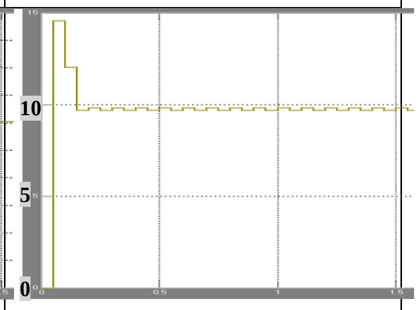
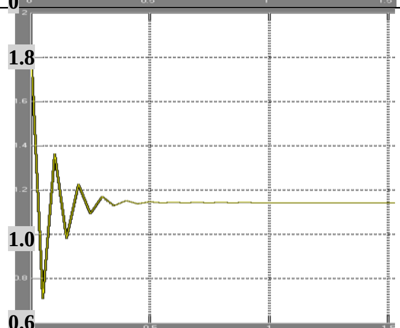
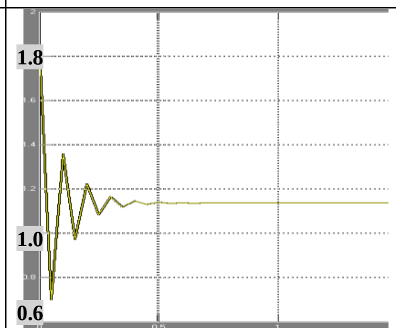
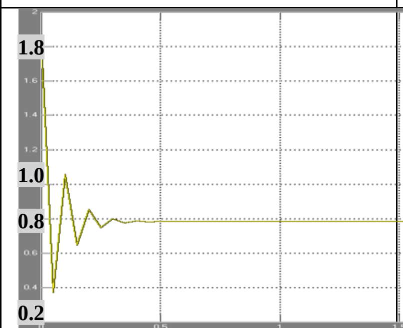
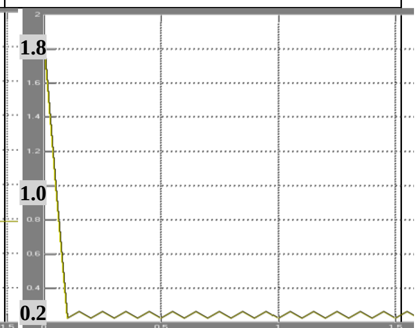
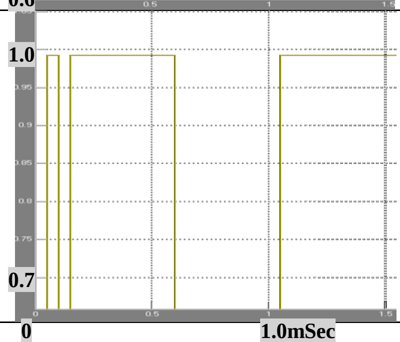
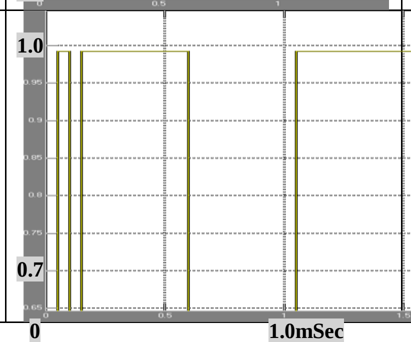
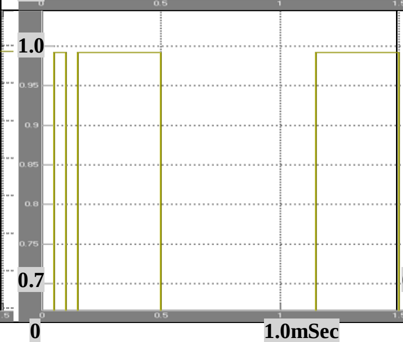
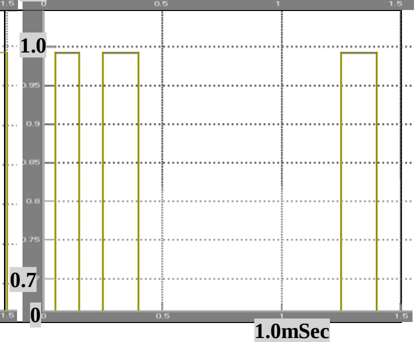
The results were obtained from the time based graphical representation of the simulation on three scopes of the MATLAB Simulink simulation model. The results are in wave forms of the various signals at specific monitoring points using the model scopes. The results are presented in form of scopes’ screenshots and same displayed in table format for column-wise comparison purposes. The results are further displayed in line graph 4.5, where the y-axis represents values of the indoor light intensity, the LEDs fuzzy logic controller output, and the window shade position fuzzy logic controller output gain factor. The x-axis of the line graph represents the values of the outdoor light intensity. Graph set 4.6 displays wave forms of output signal where a 100Hz sinusoidal varying signal, with amplitude of 10, was used for the outdoor light intensity level values.

Table 4.3: Constant values on effects of Outdoor Light intensity levels

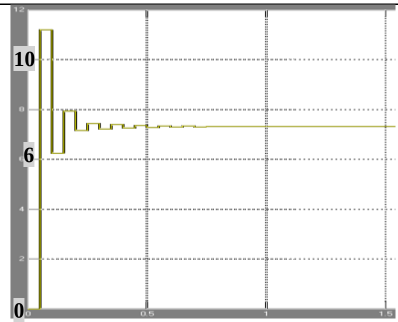
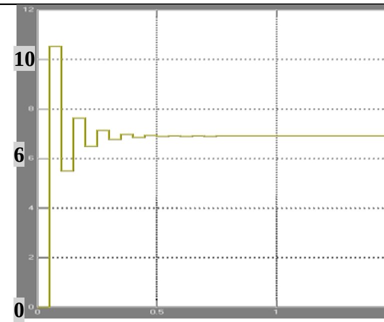
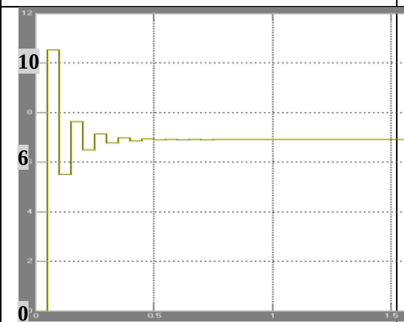
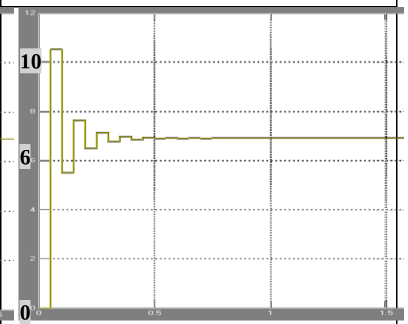
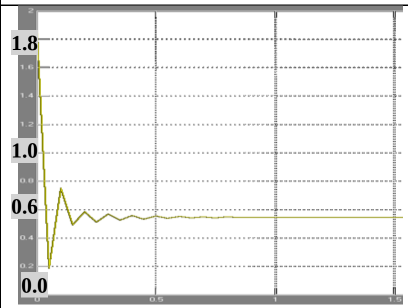
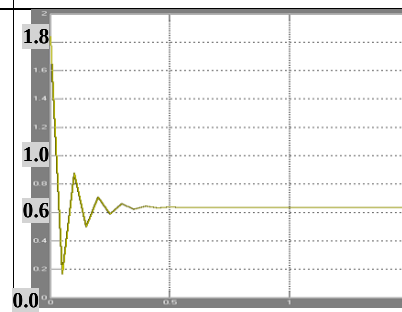
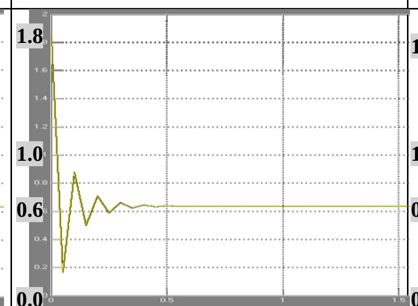
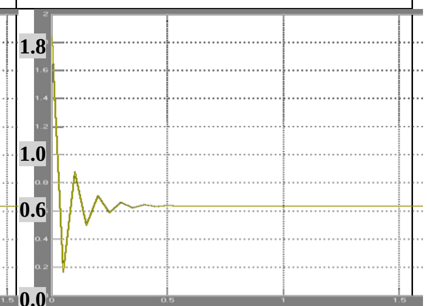
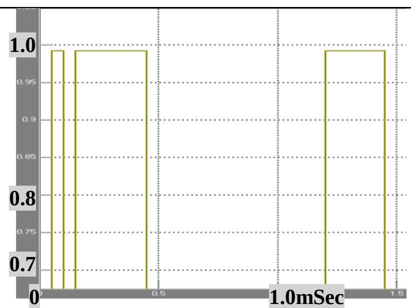
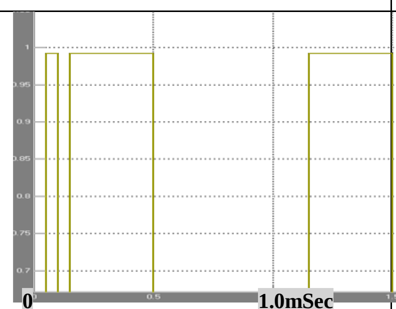
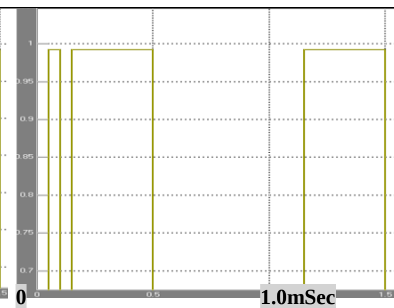
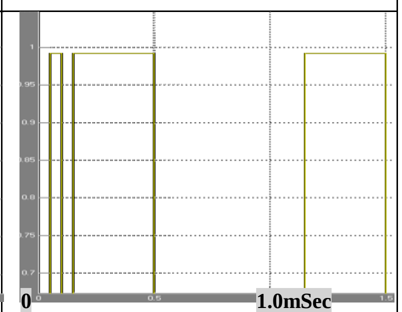
Rate of change of the indoor light level gain factor	Red colour part value	Green colour part value	Blue colour part value	Movement detector value	Number entering room	Number leaving room	Window shade position gain factor	LED light control sum gain factor
0	1	1	1	1	2	1	10	1

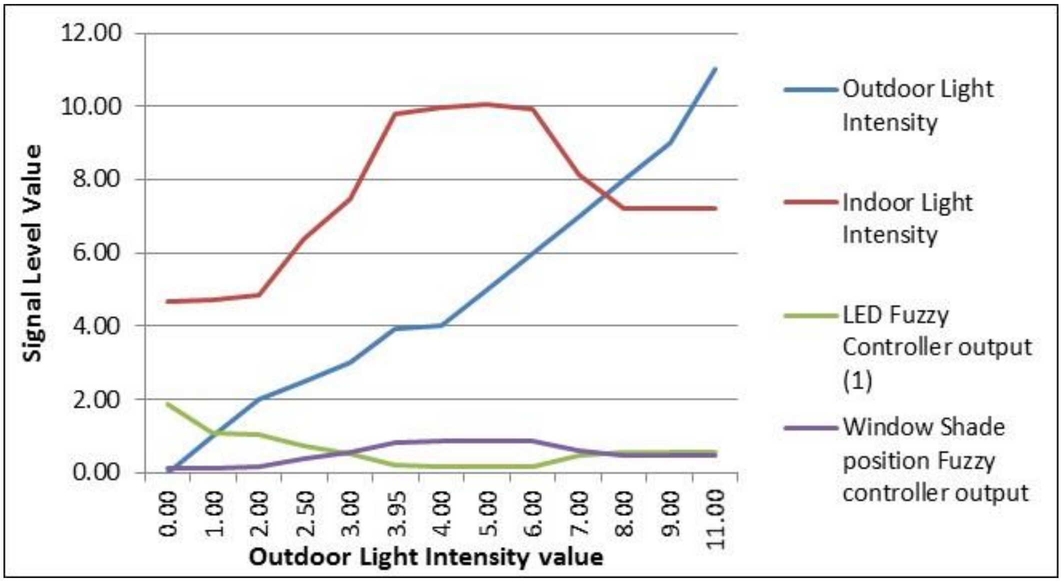
Graph set 4.4 and graph set 4.6, together with the line graph 4.5, show that the indoor illumination level values increase with increase of the outdoor light intensity but following the window shade opening position fuzzy logic controller rules. At very low outdoor light intensity levels, less than value 2, the window shade opening signal is also low, at about 0.18. At middle levels of the outdoor light intensity, about 4 to 6 values, the window shade opening signal is at maximum, about 0.9. At high levels of the outdoor light intensity, about 8 to 10 values, the window shade opening signal is at middle position, about 0.7.

Graph set 4.4: Screenshots – Effects of Outdoor Light intensity values- Comparing graphical shapes and values

	Outdoor Light signal level of 0	Outdoor Light signal level of 1	Outdoor Light signal level of 2.5	Outdoor Light signal level of 5
Indoor light level feedback signal				
Output of the LED light intensity fuzzy logic controller				
Red LED current pulses				

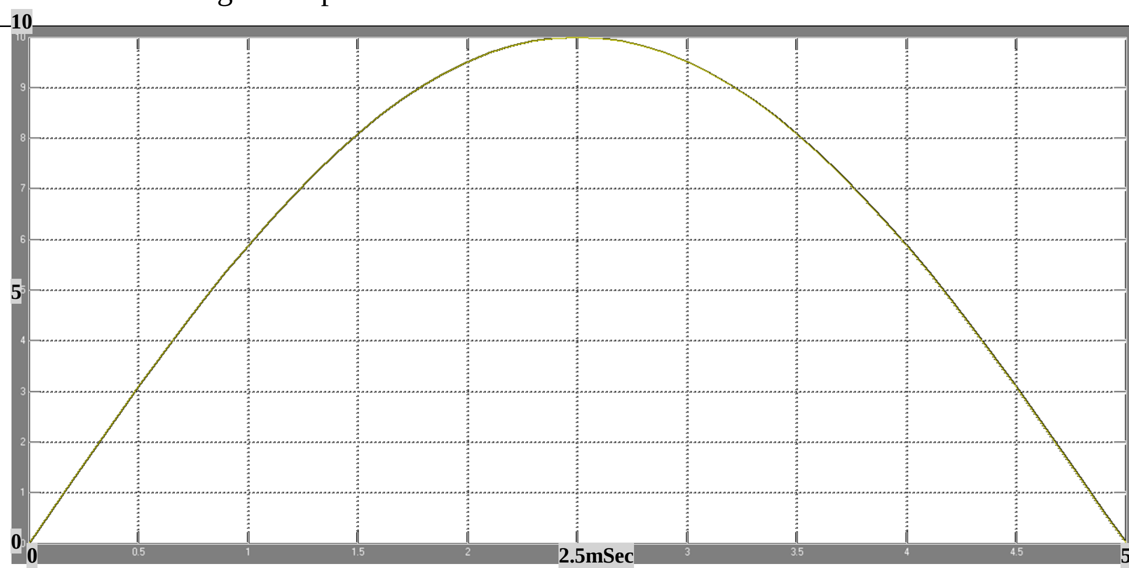
Graph set 4.4 – Cont…

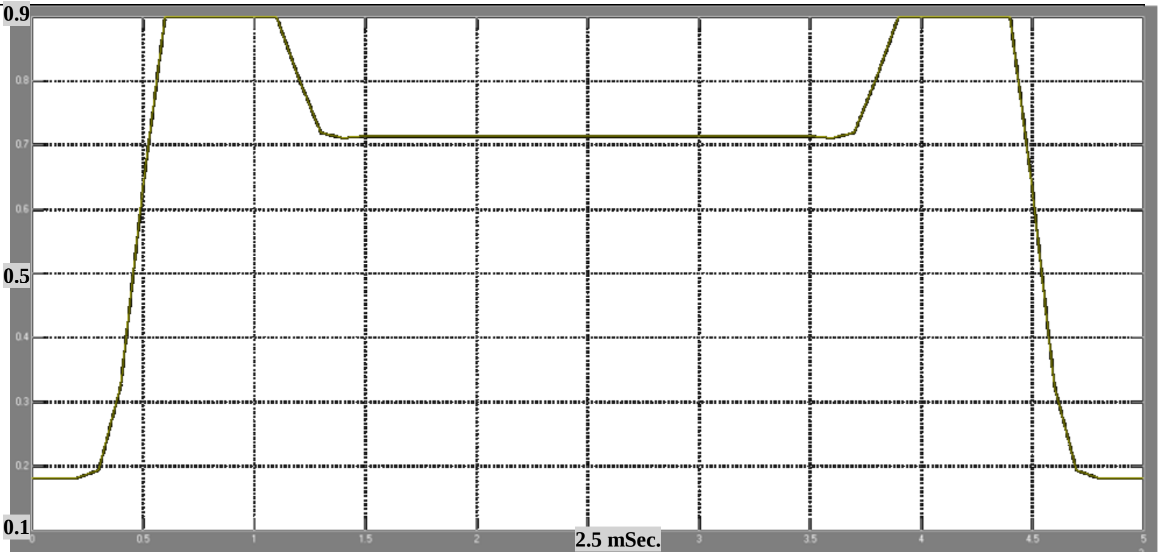
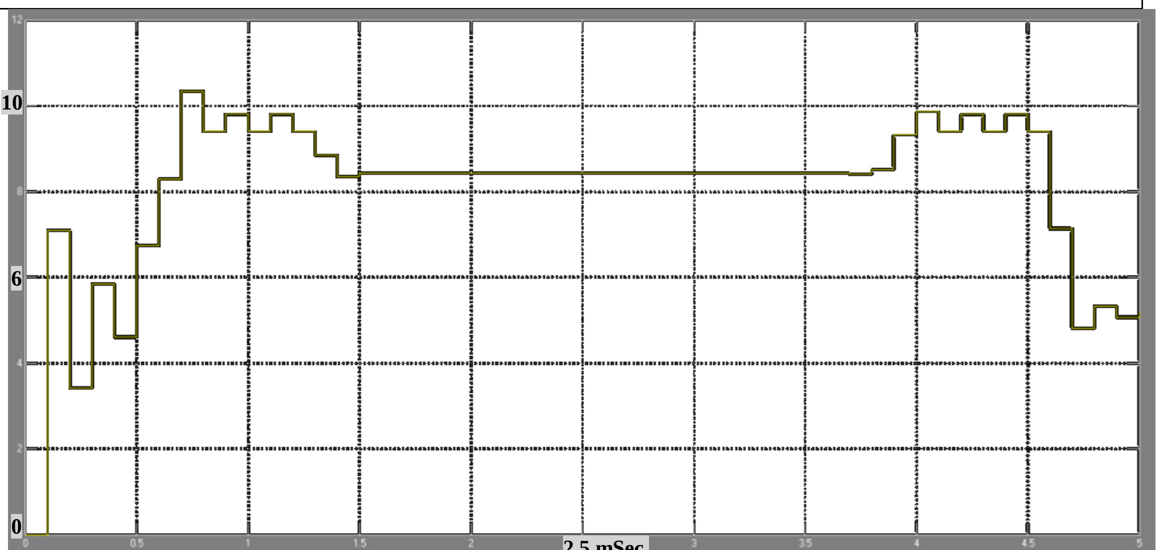
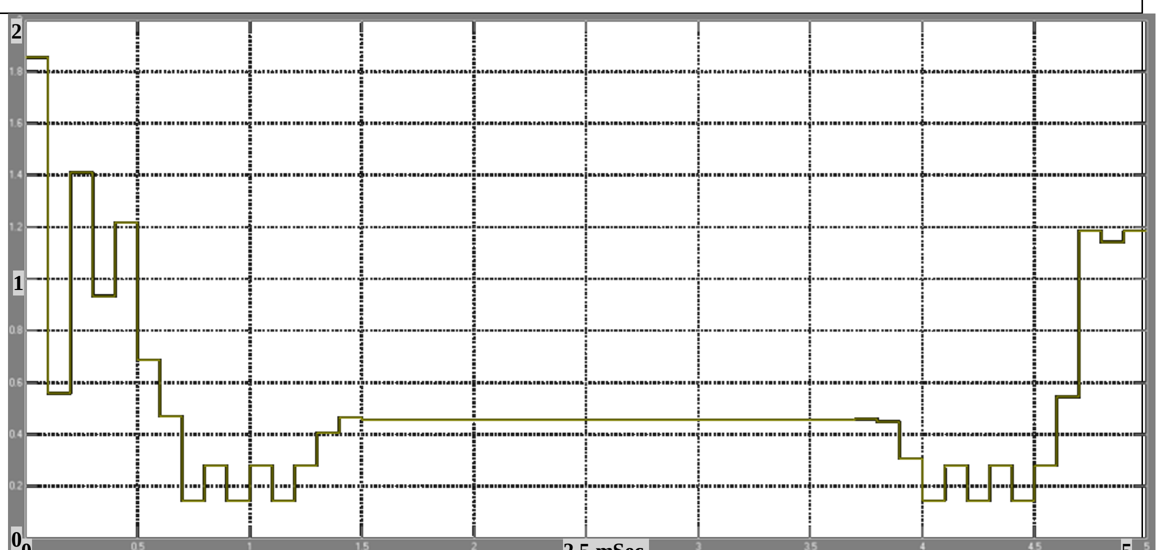
	Outdoor Light signal level of 7.5	Outdoor Light signal level of 10	Outdoor Light signal level of 11	Outdoor Light signal level of 20
Indoor light level feedback signal				
Output of the LED light intensity fuzzy logic controller				
Red LED current pulses				



Graph 4.5: Line graph – effect of the outdoor light intensity level signal on other output signals.

Graph set 4.6: Set of screenshots – Effects of sinusoidal signal for Outdoor Light intensity values-Wave forms

Signal	Wave form of signal outputs
Input signal as outdoor light level Sin signal, 100Hz, amplitude of 10.	

Window shade opening fuzzy logic controller output signal	
Indoor lighting level feedback signal	
LED average power fuzzy logic controller output.	

4.4.2 Discussion on effect of outdoor light intensity level on indoor illumination levels and the LEDs' output.

The objective of checking how various values of the outdoor light intensity affect the model's functions was successful. The window shade position fuzzy logic controller output signal behaved as expected. Graph 4.6 show that window controller output signal smoothly rise from low values to high values, then lowers to mid values. It was also noted that there are three flat sections on widow shade controller output graphs; the window shade closed position with output value of about 0.18, the fully open position with output value of about 0.9, and the mid open position with output value of about 0.7. This confirmed that the window shade position fuzzy logic controller was operating in response to the "if-then" control rules set out in table 3.1 in chapter 3.

The LEDs fuzzy logic controller output signal was also noted to follow the indoor illumination levels but in a contrasting manner; as the indoor light intensity increases, the LEDs controller output signal decreases. The indoor light intensity signal was noted to oscillate at particular outdoor light signal levels. This indoor lighting oscillation behavior was as expected; the LEDs fuzzy logic controller trying to meet the room's light level requirements in the closed loop control signal circuit.

The test also confirmed that the LEDs' current pulse width was increasing with the LEDs fuzzy logic controller output signal level and vice-versa. The line graph 4.5 confirms that when the outdoor light contribution is zero, the LEDs fuzzy logic controller output signal is at highest level and hence LEDs output luminance level. When the window shade opening signal level is highest, the corresponding LEDs fuzzy logic controller output signal level is, in contrast, the lowest. This is as was expected and confirms that the design model was functional and effective in saving electric energy for lighting a typical room when the outdoor daylight is available.

The fuzzy logic controllers do not provide the expected absolute lowest set signal values, i.e. 0, or the highest set values, 1 for the window shade controller and 2 for the LEDs controller. This problem was noted as weakness with fuzzy logic controllers, due to their approximation (defuzzificztion) approach.

4.5 Effect of Different Level Values of the Red, Green and Blue Colour Portions

The objective of this test was to confirm the model's ability to calculate ratio values of the primary colour (red, green, and blue) levels, reproduce a signal that represents the whiteness of the selected light (colour product) which is used as an input to the window shade position fuzzy logic controller. It was expected that for white light signal value, the product of the colour ratios, would be about 1. Coloured light signal values were expected to have colour ratio product of less than 0.8.

The other objective of this test was to confirm if the system model could use the primary colour ratios to determine the respective RGB LEDs current pulse width. It was expected that for smallest colour ratio, the respective colour LED current pulse width would also be the narrowest. The highest colour ratio value was expected to be 1 and the respective colour LED current pulse width would be widest and directly proportional to the controlling signal value from the LEDs fuzzy logic controller.

The colour ratio product was also expected to close the window shade if its signal value is less than 0.8. Contribution of the LEDs light to the room illumination levels was expected to be proportional to the colour ratio product.

4.5.1 Results of testing effect of different level values of colour portions on indoor illumination levels and the width of the LEDs' current pulses.

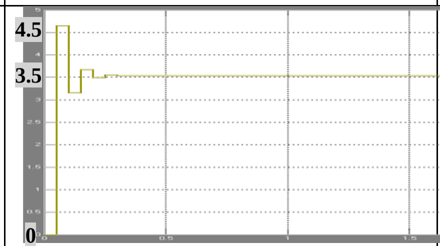
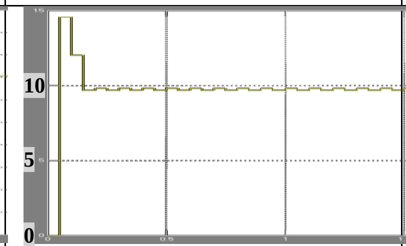
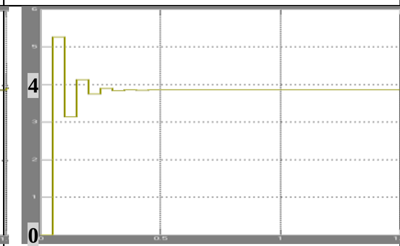
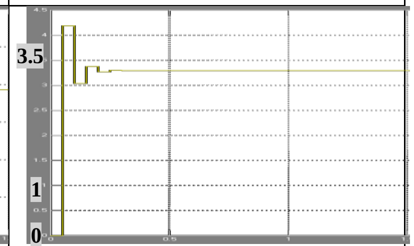
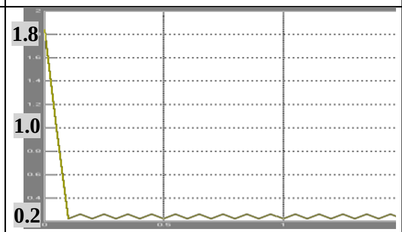
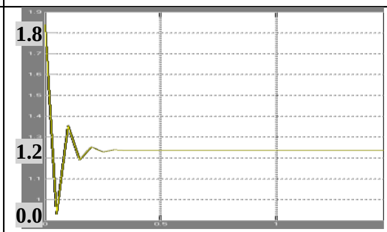
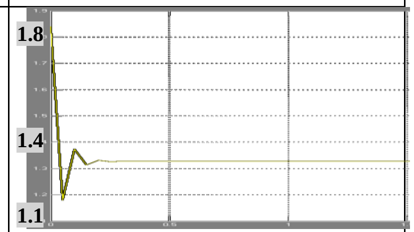
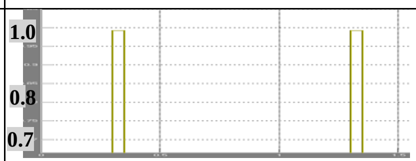
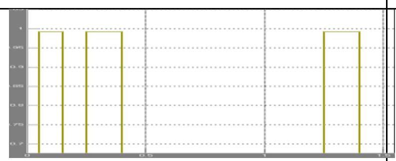
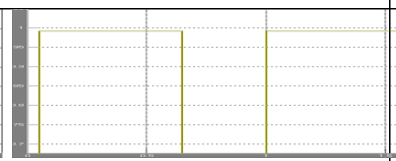
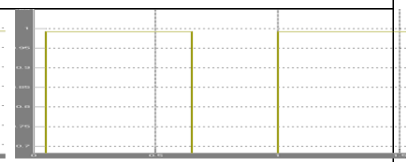
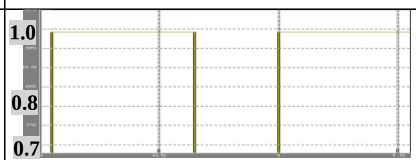
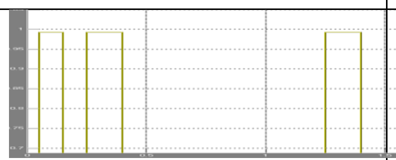
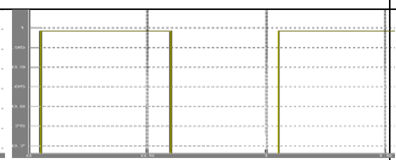
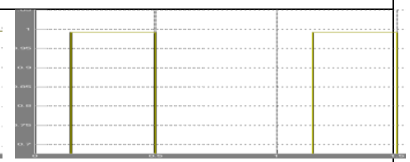
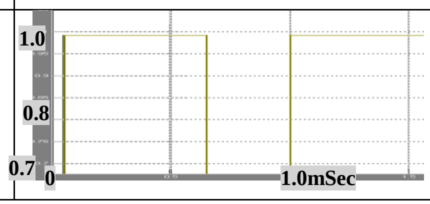
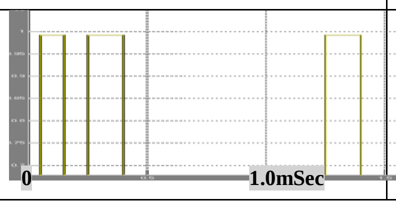
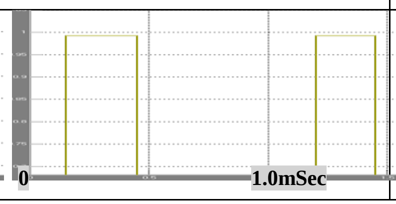
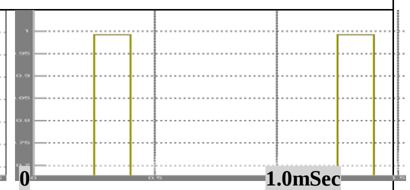
The test was carried out using varying values of the three colour portions but at constant value of the outdoor light intensity of 5, constant value of the window shade fuzzy logic controller output gain factor of 10, constant zero value for rate of change of the indoor light intensity, enabled room movement detector, and enabled room occupancy. The simulation model data values were as shown in table 4.4. Graph set 4.7 compares the wave forms of indoor illumination level signal, and output of the LED light intensity fuzzy logic controller, and the current pulse widths of each of the three red, green and blue LEDs for various values of the input red/green/blue colour portions. Graph 4.8 is a line graph showing the relationship of the various values of the red/green/blue colour portions with their ratio product, "colour product". Graph 4.9 is a line graph showing the relationship of the red/green/blue portion value, colour ratio product signal and the window shade controller output and the LEDs' controller output signals. Graph 4.10 is also a line graph showing the relationship of the various values of the red/green/blue colour portions and their respective signals for each colour

LED's PWM generator. The results were obtained from the time based graphical representation of the simulation on various signal level monitoring points in the simulation model. The results are in wave forms of the various signals at specific monitoring points using the model scopes. The results are presented in form of scopes' screenshots. The wave forms are displayed in table format for column-wise comparison purposes. The respective values extracted from the appropriate scopes were tabulated and displayed in line graphs where the y-axis represents values and the x-axis represents the colour product signal values.

Table 4.4: Constant values- Effect different signal levels of colour red, green, blue portions.

Outdoor light level value	Red colour part value	Green colour part value	Blue colour part value	Rate of change of indoor light intensity gain factor	Movement detector value	Number entering room	Number leaving room	Window shade position gain factor value	LED light control sum gain factor value
5	-	-	-	0	1	2	1	10	1

Graph set 4.7: Set of screen shots of respective scopes- Effect of different values of the red, green and blue colour portion signal levels.

	Colour levels Red=0:Green=1:Blue=1	Colour levels Red=0.5:Green=0.5:Blue=0.5	Colour levels Red=0.9:Green=0.8:Blue=0.4	Colour levels Red=1:Green=0.5:Blue=0.25
Indoor light level feedback signal				
Output of the LED light intensity fuzzy logic controller				
Red LED current pulses				
Green LED current pulses				
Blue LED current pulses				

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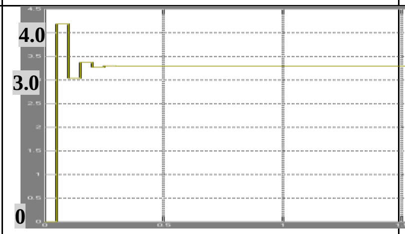
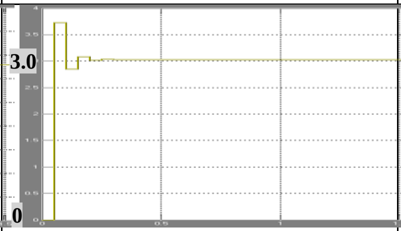
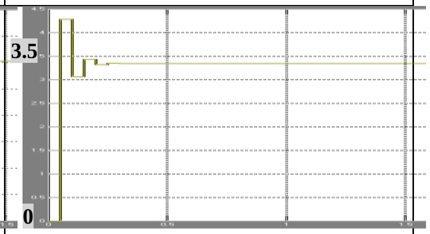
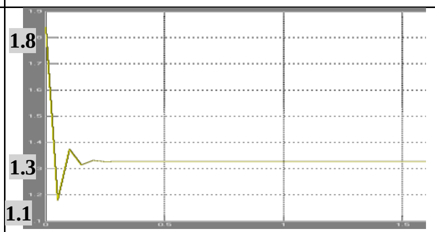
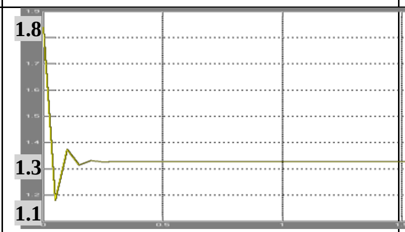
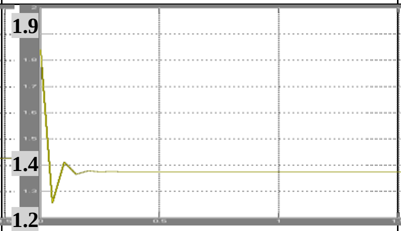
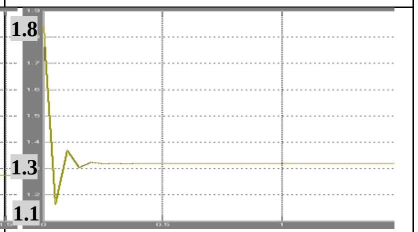
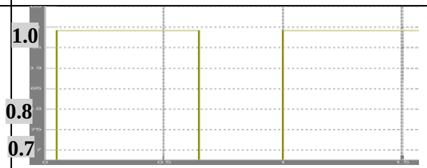
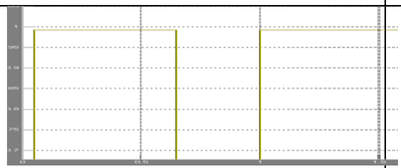
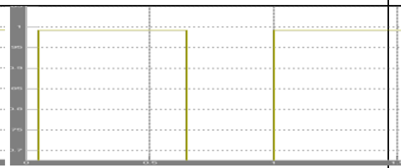
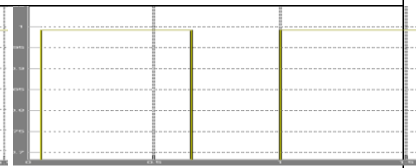
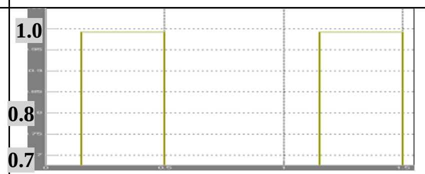
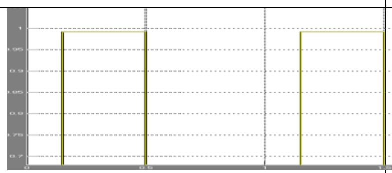
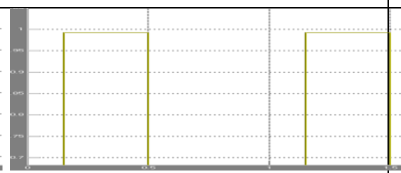
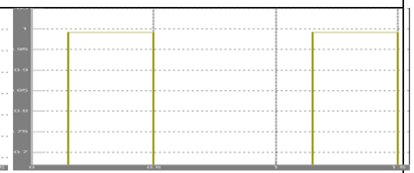
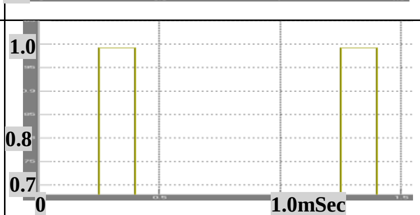
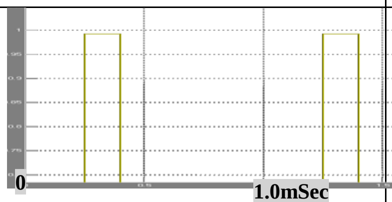
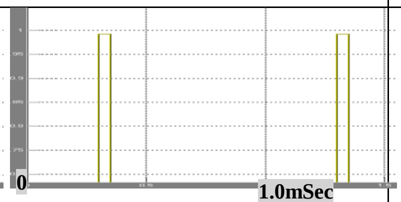
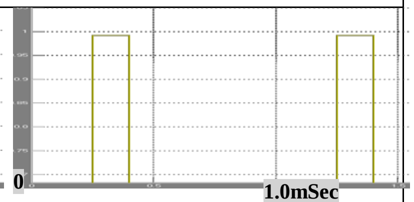
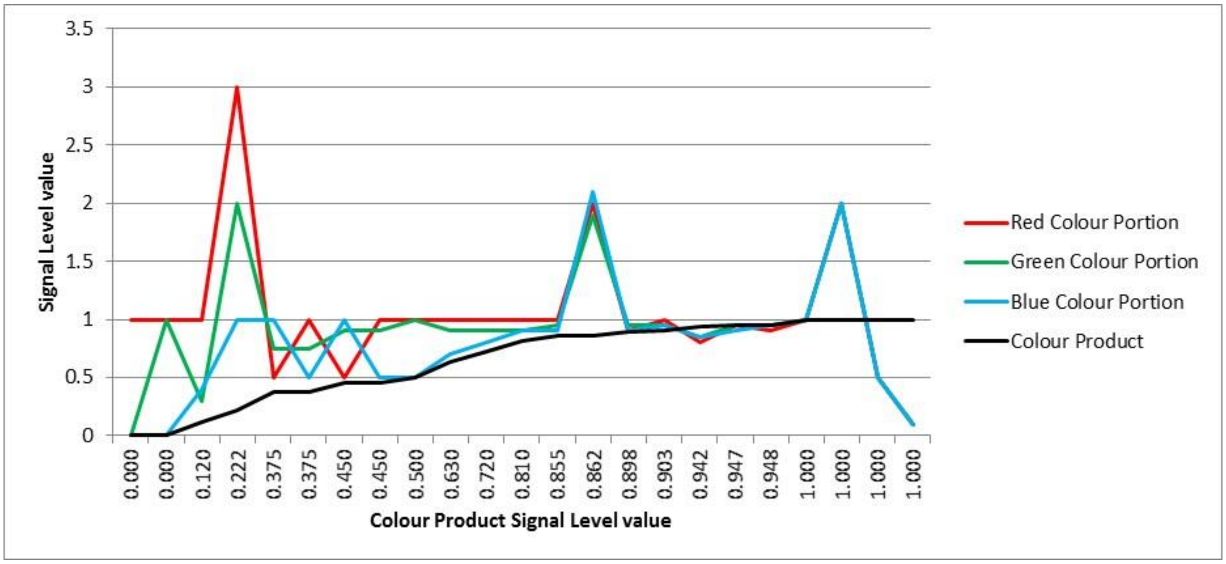
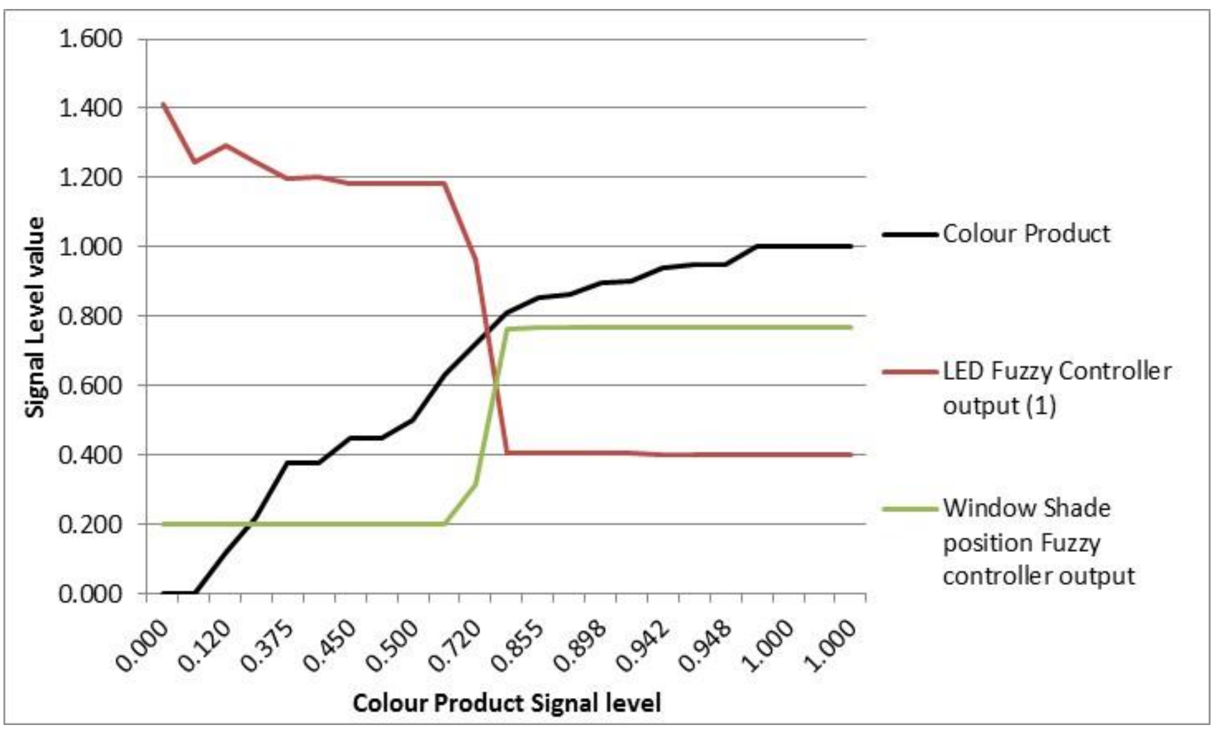
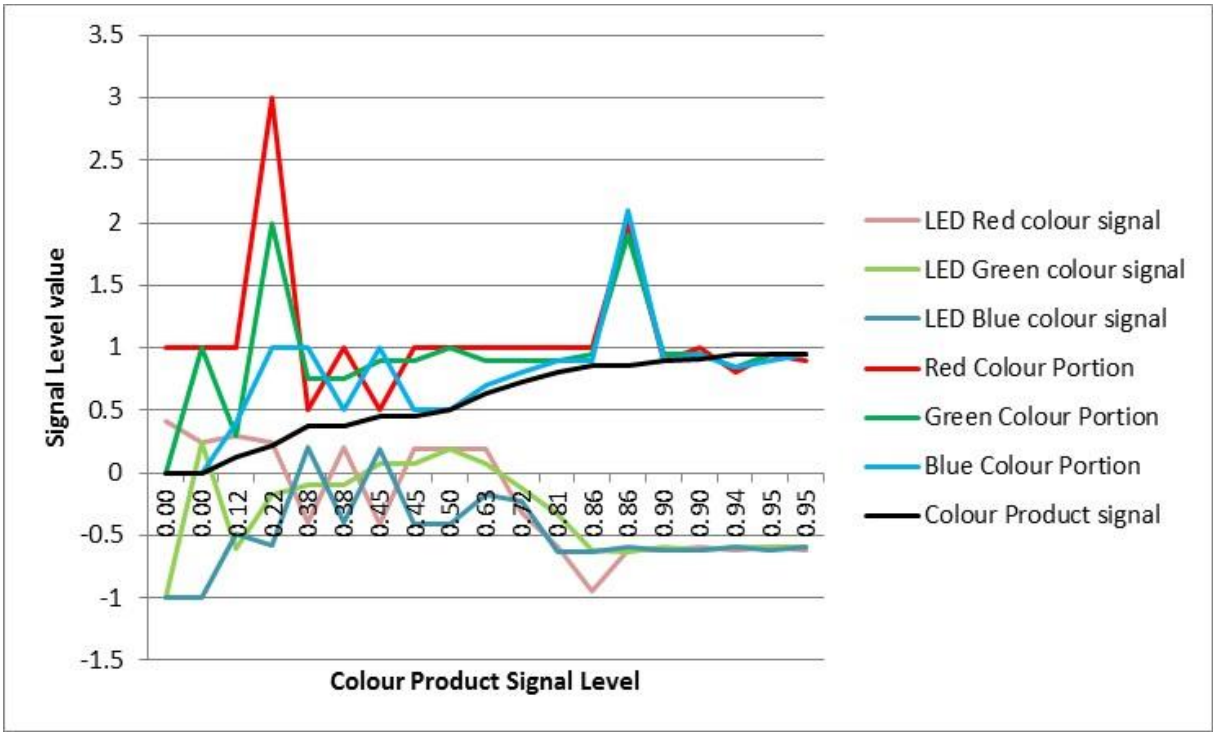
	Colour levels Red=3:Green=1.5:Blue=0.75	Colour levels Red=0.5:Green=0.25:Blue=0.125	Colour levels Red=1:Green=0.5:Blue=0	Colour levels Red=0.05:Green=0.025:Blue=0.015
Indoor light level feedback signal				
Output of the LED light intensity fuzzy logic controller				
Red LED current pulses				
Green LED current pulses				
Blue LED current pulses				



Graph 4.8: Line graph – Effect of Red, Green, and Blue values on colour product signal



Graph 4.9: Line graph – Effect of white light signal on window shade controller output



Graph 4.10: Line graph –Effect of Red, Green, and Blue colour portions on respective PWM generator input signal level

'Colour product' is a term used to represent the product (multiplication) of the three colour portion calculated ratios. Colour product signal level value is a measure of the whiteness of the LEDs output light. For colour product signal level value of 0.80 to 1, the LEDs'output light is considered white and the window shade may open depending on the outdoor light intensity.

Graph set 4.7 of screenshots show that even though the outdoor light intensity is constant at signal level value of 5, the window shade opening position is determined by the colour product signal level value. For colour product signal value of about 0, the indoor illuminance is low, about 3.5, and the LEDs fuzzy logic controller output signal value is highest at about 1.35. The LEDs' respective current pulse width is most narrow for the corresponding colour portion with almost zero value but widest for the colour portion with largest value. This demonstrates that each colour LED's average power output is proportional to fraction of its respective colour portion level value.

Graph 4.8 is a line graph, which show that when the three red/green/blue colour portion level values are far apart their fraction product tends to 0, but when the values are close their fraction product tends to value of 1. Line graph 4.9 show that when the colour product values are low, from 0 to 0.6, the window shade is closed. But colour product signal values are from 0.8 to 1, the window shade is open. This demonstrates that the lighting system model window shade opens only when the decoded colour signal is confirmed to be from a white light.

Graph 4.10 shows the relationship of the three colour portions and their corresponding colour signals for controlling the respective LEDs' PWM pulse generators. This graph shows that the respective LEDs' PWM pulse generator input signal is fraction of the LEDs fuzzy logic controller signal, which is less by a constant value of 1 but of a pattern similar to that of the colour decoder signal level values. Negative PWM generator input values, represent narrower LED's current pulse widths.

4.5.2 Discussion on effect of different level values of colour portions on indoor illumination levels and the width of the LEDs' current pulses.

The test confirmed that the model is able to calculate ratio values of the primary colours (red, green, and blue), and the colour ratio product signal used as an input to the window shade position fuzzy logic controller. The model could recognize required LEDs' output white light and open the window shade for the daylight to enter in the room. White light signal was confirmed to have colour ratio product value of more than 0.8.

The test also confirmed that model design could use the primary colour ratios to determine the respective RGB LEDs current pulse width, and hence the LEDs' output light colour. The smaller the colour ratio, the narrower the respective colour LED current pulse width would be. The smaller the LEDs current pulse width, the less the intensity of light (luminance) from the respective LED. Hence the colour ratio signal value for each respective primary colours determine the overall colour of the combined light from the three RGB LEDs.

The system design model demonstrated that it can effectively control colour of light produced by the RGB LEDs in a typical room, and at the same time allow daylight to be used in the room if only white light is required, saving electric lighting energy. The lighting system design simulation, also demonstrated that it is sensitive to the room user's needs for coloured light by closing the window shades, even during day time, and prevent interference of the room's required lighting colour from the more bright outdoor white daylight.

4.6 Cause and effect of absence of Colour Decoder, Movement Detector, and Room Occupancy Signals.

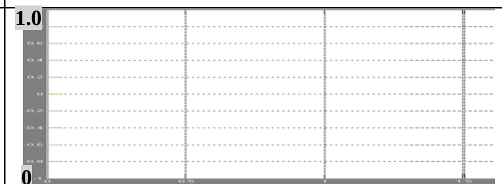
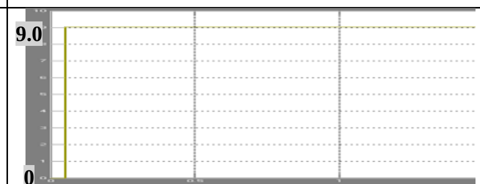
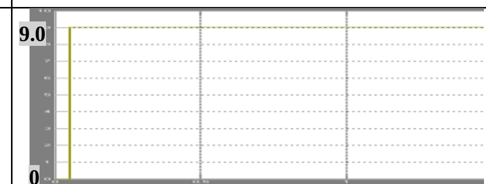
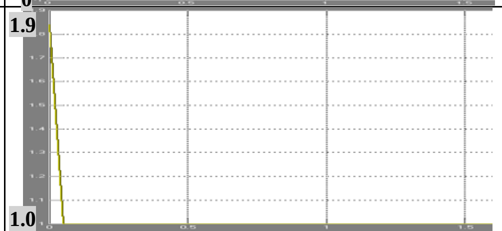
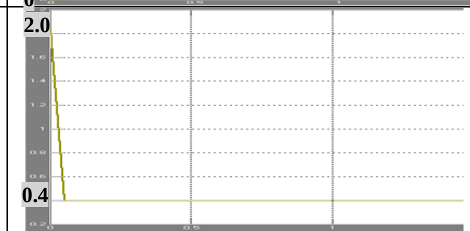
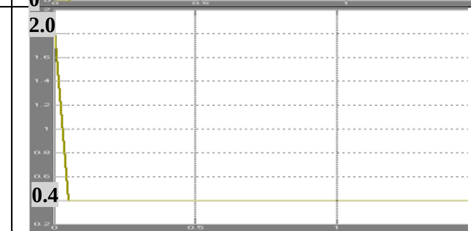
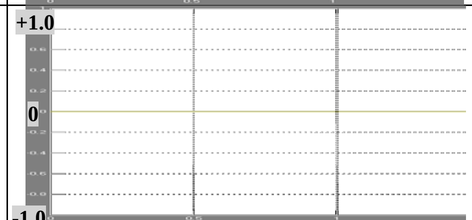
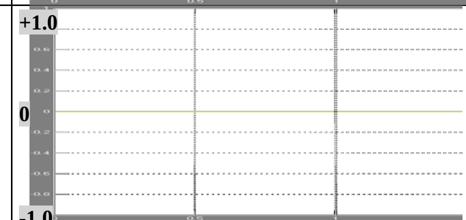
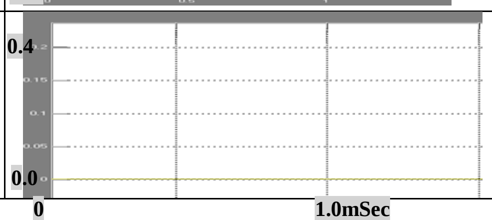
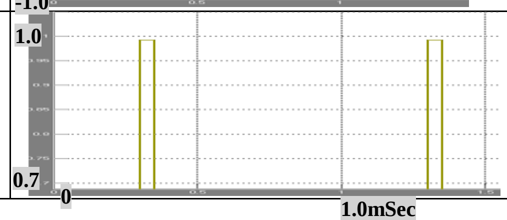
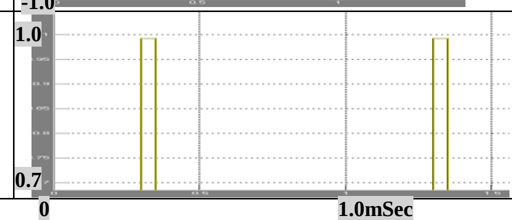
The objective of this test was to check and confirm if the system model could actually switch off the LEDs by means of a signal level value from either the colour decoder (selector), or the movement (motion) detector, or the room occupancy counter. This test was based on signal enabler switches put in series with the output signal circuit from the LEDs fuzzy logic controller as shown in figure 3.35, a section of the lighting system model in chapter 3. This test was also to confirm that absence of the respective sensor output signal is caused by lack of activation on the sensor input for the colour decoder, and the movement detector. The room occupancy counter output signal is determined by arithmetic difference of the entry and exit counter readings.

It was expected that if a signal level value from either of the three sensors; colour decoder, movement detector, and the room occupancy, is less than 0.5 (a set value for activating each enabler switch), then the LEDs fuzzy logic controller output signal could automatically be blocked and the affected enabler-switch output signal value turned to zero and hence switch off the LEDs.

4.6.1 Results of testing cause and effect of absence of the colour decoder, movement detector, and room occupancy signals.

The test was carried out using the following parameters maintained constant: outdoor light intensity of 5, window shade fuzzy logic controller output gain factor of 10, rate of change of the indoor light intensity at 0. The simulation test was done for the colour decoder, the movement detector, and the room occupancy. For the colour decoder, the three primary colour portion inputs were each given zero value, the movement detector input given 1, and the room occupancy counter inputs given 2 and 1 for entrance and exit respectively. The colour signal enabler switch output was expected to have zero value and the LEDs' output current pulse width to be very narrow. Same test was repeated for movement detection and the room occupancy respectively. Graph set 4.11 compares the wave forms of indoor illumination level signal, and output of the LED light intensity fuzzy logic controller, and the current pulses for the red LED (as a representative of the three LEDs). The screenshot waveforms for the red LED's current pulses are compared for the three tests.

Graph set 4.11: Set of screenshots of the respective scopes – Effect of zero values of colour portions (c_s) (colour white signal), movement detector signal (M_d), and room occupancy signal (R_o).

	Red=0:Green=0:Blue=0 Room occupancy =1 Movement detection signal=1 (Testing effect of no colour signal)	Red=1:Green=1:Blue=1 Room occupancy =1 Movement detection signal=0 (Testing effect of no movement detection signal)	Red=1:Green=1:Blue=1 Room occupancy =0 Movement detection signal=1 (Testing effect of no room occupancy signal)
Indoor light level feedback signal			
Output of the LED light intensity fuzzy logic controller			
Output -2 of the LED light intensity fuzzy logic controller			
Red/Green/ Blue LED current pulses			

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The waveforms displayed in graph set 4.11 show that the signal output (output 2) of the LEDs' output fuzzy logic controller, after the enabler switches, is zero for the three tests.

It was noted that when the three colour portion values are zero, then the lighting system model does not give any signal at the white light signal input to the window shade position controller as well as to the LEDs controller. The room feedback signal disappears, and the LED's current pulses do not occur. However, when the movement detector or the room occupancy signals is zero, the system functions well with zero value for each colour signal to the PWM pulse generator and the LED's current pulses occur though with very thin width.

4.6.2 Discussion on effect of zero values of the colour decoder signal, movement detector signal, and room occupancy signal.

The expectations of this test were partially met. The system model could actually switch off the LEDs by means of a signal value level from the colour decoder, or from the movement detector, or from the room occupancy counter. However, the colour decoder signal was noted to disturb the system's signal flows. This could be associated with the system design defect. The enabler switch for the colour decoder signal may not have been necessary. The LEDs control signal distribution through the colour ratio multiplier shown in figure 3.37 in chapter 3, also produces zero signal value when the respective colour ratio signal value is zero and this could cause mathematical simulation problem.

It was also noted that the respective LED's current pulse width could not be exactly zero as expected for -1 input to the PWM generator. This problem could be associated with the fact that the PWM pulse generators (PWM red, PWM green and PWM blue) shown in figure 3.38 of chapter 3 are not ideal; cannot give zero width pulses.

4.7 Effect of Too High, Moderate, Low and Negative Values of Outdoor Light

The objective of this test was to check and confirm if signal from the outdoor light intensity sensor with values outside the set range of the window shade fuzzy logic controller membership function configuration does really affect the system's controllability.

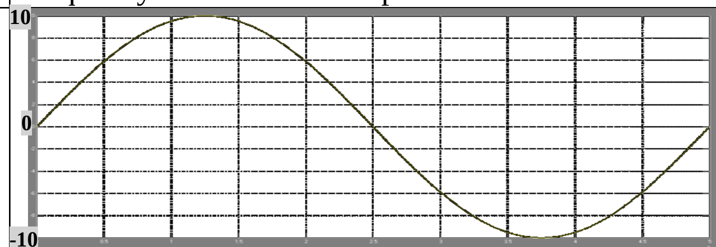
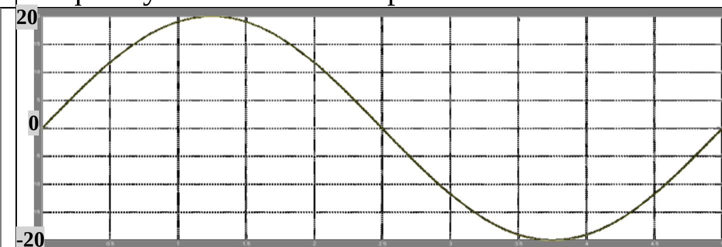
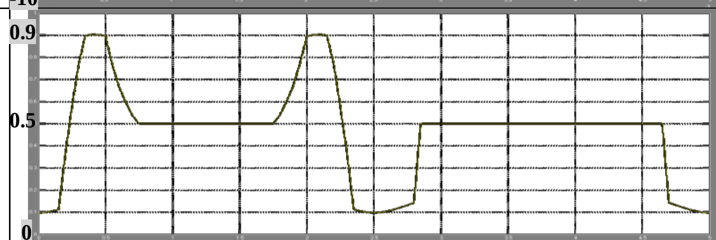
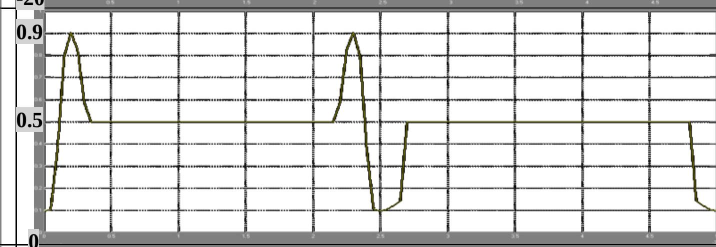
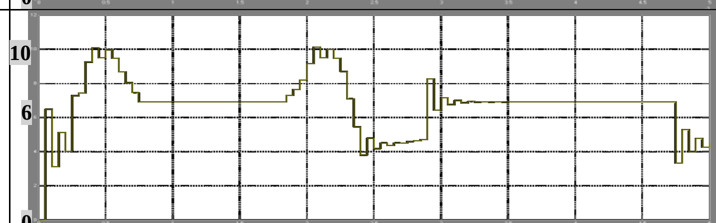
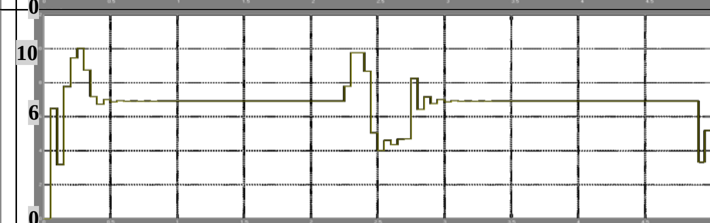
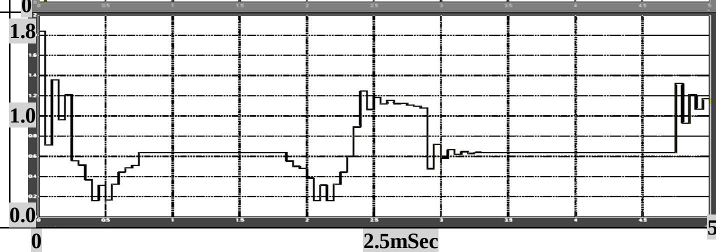
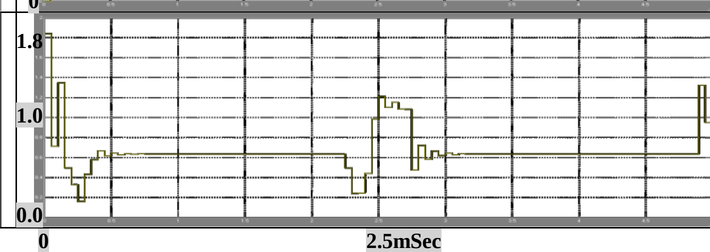
The output signal from the window shade position fuzzy logic controller was expected to be of a constant value, same as one before outdoor light signal level had changed, without changing with change of the outdoor light signal value that lies outside the preset controller membership function range shown in figures 3.18 and 3.19 in chapter 3.

4.7.1 Results of testing effect of too high, moderate, very low, and negative values of outdoor light intensity on window shade controller output signal, indoor illumination levels, and the LEDs' controller output.

The test was carried out using a 200Hz sinusoidal signal generator as the outdoor light intensity signal source. The other system parameters were maintained constant with the values for each red/green/blue input colour portion levels at 1, value of the window shade fuzzy logic controller output gain factor of 10, zero value for rate of change of the indoor light intensity, enabled room movement detector, and enabled room occupancy. The 200Hz sinusoidal signal was used for various amplitudes. The test result graph set 4.12, graph set 4.13, and graph set 4.14 were used for comparing the waveforms of the outdoor light intensity signal, the window shade position controller output signal, indoor illumination level signal, and the LEDs' light intensity fuzzy logic controller output signal.

The results were obtained from the time based graphical representation of the simulation on various specific scopes of the MATLAB Simulink simulation model. The results are in waveforms of the various signals at specific monitoring points using the model scopes. The results are presented in form of the scopes' screenshots. The waveforms are displayed in table for column-wise comparison purposes. Graph set 4.12 compares effect of outdoor light intensity of sinusoidal signal amplitude of 10 with that of 20. Graph set 4.13 compares signal amplitude of 10 with that of 7, while graph set 4.14 compares outdoor light signal amplitude of 10 with that of 3.

Graph set 4.12: Set of screen shots- Effect of too high outdoor light intensity signal – Positive and negative input signals

	Outdoor Light intensity sinusoidal signal with frequency of 200Hz and amplitude of **10**	Outdoor Light intensity sinusoidal signal with frequency of 200Hz and amplitude of **20**
Outdoor light - Input signal. Amplitude =10 and 20 for comparison		
Window shade position fuzzy logic controller output		
Indoor (room) light level		
Indoor LED light level fuzzy logic controller output		

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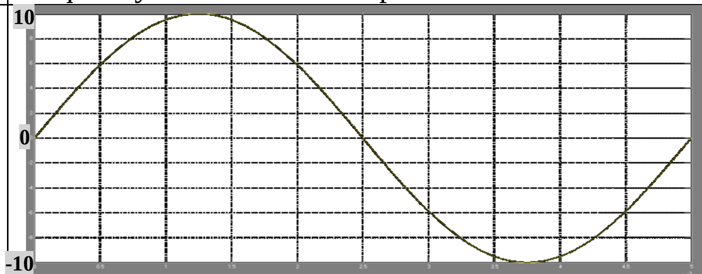
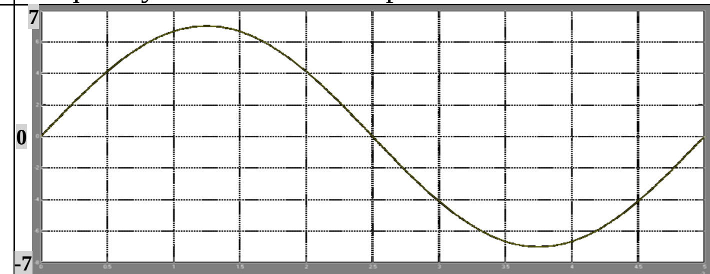
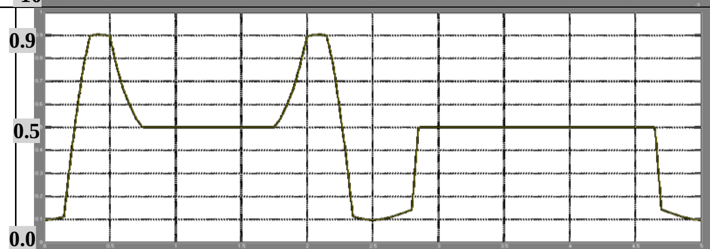
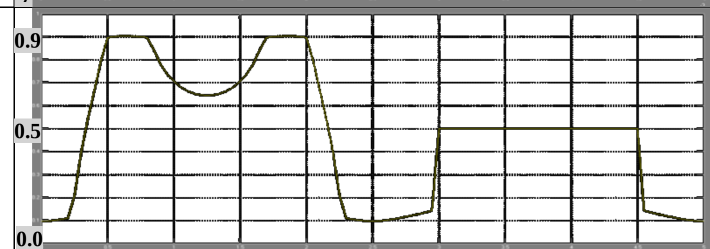
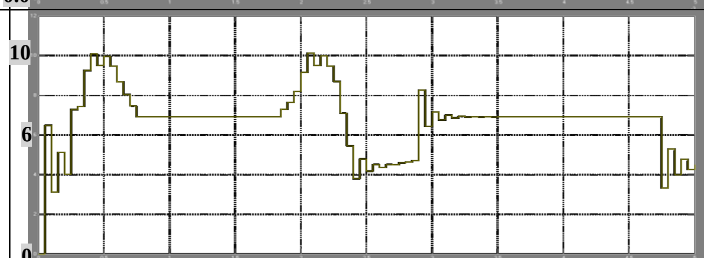
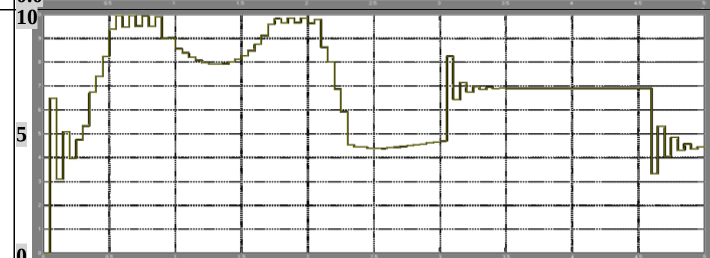
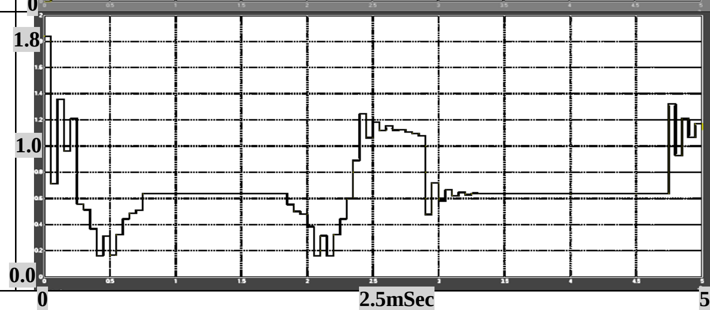
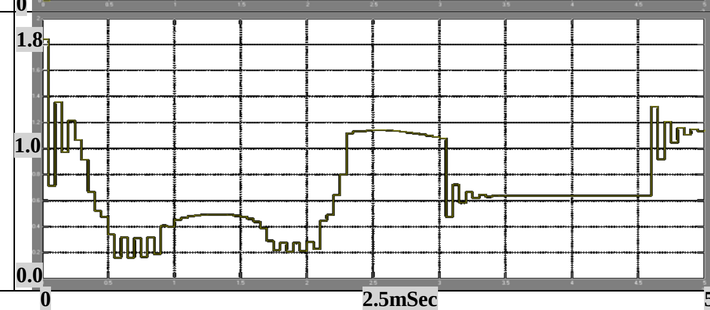
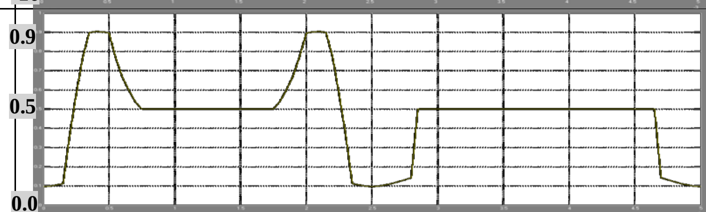
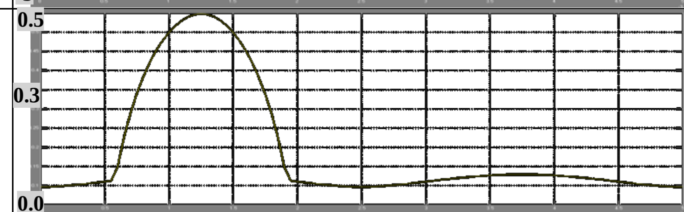
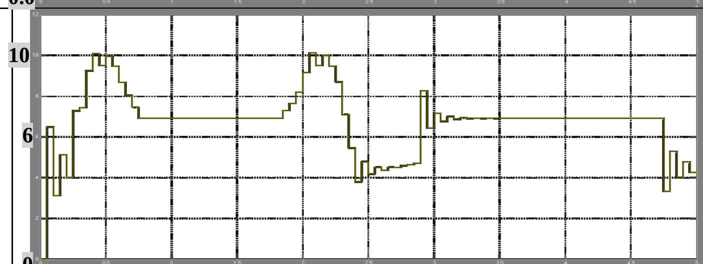
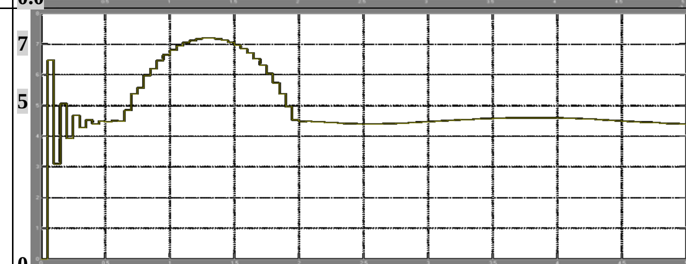
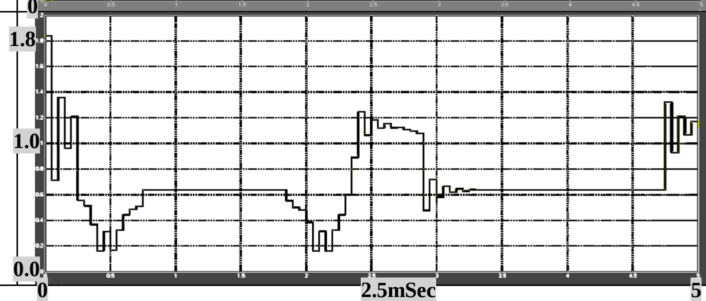
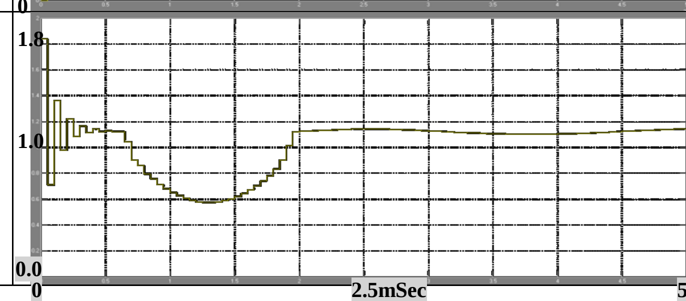
Graph set 4.13: Set of screen shots – Effect of moderate outdoor light intensity signal values – Positive and negative signals

	Outdoor Light intensity sinusoidal signal with frequency of 200Hz and amplitude of **10**	Outdoor Light intensity sinusoidal signal with frequency of 200Hz and amplitude of **7**
Outdoor light - Input signal. Amplitude =10 and 7 for comparison		
Window shade position fuzzy logic controller output		
Indoor (room) light level		
Indoor LED light level fuzzy logic controller output		

Graph set 4.14: Set of screenshots – Effect of low outdoor light intensity signal values- Positive and negative signals

	Outdoor Light intensity sinusoidal signal with frequency of 200Hz and amplitude of **10**	Outdoor Light intensity sinusoidal signal with frequency of 200Hz and amplitude of **3**
Outdoor light - Input signal. Amplitude =10 and 3 for comparison		
Window shade position fuzzy logic controller output		
Indoor (room) light level		
Indoor LED light level fuzzy logic controller output		

The wave forms displayed in graph set 4.12, where effect of outdoor light sinusoidal signal with amplitude of 10 is compared with that of 20, show that the window shade position controller output signal is low at low outdoor light input signal and rises to maximum value of 0.9 as the outdoor light signal passes through the 4 to 6 level values then falls to mid position value of 0.5 for any other values of outdoor light intensity beyond 9. This observation is true for both signals with amplitude of 10 and that of 20. The indoor illumination level values follow the curve form of the window shade position controller output. The LEDs' fuzzy logic controller output signal is observed to effect reduction or increase of the LEDs average power output depending on the indoor illumination levels.

The wave forms displayed in graph set 4.13, where effect of sinusoidal signal with amplitude of 10 is compared with that of 7, show that the window shade position controller output signal is low at low outdoor light input signal and rises to maximum value of 0.9 as the outdoor light signal passes through the 4 to 6 level values then falls to value of about 0.7 for the values of outdoor light intensity to maximum of 7, which is the signal amplitude. This signal with amplitude of 7 does not drive the window shade position fuzzy logic controller to maximum input range, hence the controller output signal does not reach the mid position of 0.5. The indoor illumination level values follow the curve form of the window shade position controller output. The LEDs' controller output signal is observed to effect reduction or increase of the LEDs average power output depending on the indoor illumination levels.

The waveforms displayed in graph set 4.14, where effect of sinusoidal signal with amplitude of 10 is compared with that of 3, show that the window shade position controller output signal is lowest, 0.05, at low outdoor light input signal and rises to maximum value of only 0.5 as the outdoor light signal passes through the 2 to 3 level values then falls again to its lowest value of about 0.05, as the values of outdoor light intensity falls back to 0. This outdoor light signal with amplitude of 3 does not drive the window shade position fuzzy logic controller to maximum input range. The indoor illumination level values follow the curve form of the window shade position controller output. The LEDs' fuzzy logic controller output signal level is observed to rise and fall depending on the indoor illumination levels.

The values of the outdoor light intensity signal are observed to be negative after 2.5 milliseconds of the simulation start. The waveforms displayed in graph sets show that the window shade position controller output signal is always positive, and rise to mid-point constant value of 0.5, as the outdoor light input signal level falls from zero to maximum negative value for each test input signal amplitude of 7, 10, and 20. But for test input signal with amplitude of 3, the window shade position controller output signal rises to a maximum value of 0.055.

4.7.2 Discussion on effect of too high, moderate, very low, and negative values of outdoor light intensity on window shade controller output signal, indoor illumination levels, and the LEDs' controller output.

The objective of this test was fully met. The signal from the outdoor light intensity sensor with values outside the set range of the window shade fuzzy logic controller membership function configuration does really affect the lighting system's controllability. When the output signal for controlling the window shade position is affected, the indoor light levels and the feedback signal to the LEDs fuzzy logic controller are also affected.

The output signal from the window shade position fuzzy logic controller was of a constant value, mid-point value of 0.5, for almost all outdoor light signal value that lies outside the preset controller membership function range. However, for outdoor light signals with values which are just at the edge, though outside the membership function range, the fuzzy logic controller output is not constant. This phenomenon could be attributed to the shape of the end-side controller membership function plots.

The window shade position fuzzy logic controller does not correctly respond to too high or negative outdoor light intensity signal values. The test also confirms that LEDs fuzzy logic controller output signal level rises and falls in contrasting rhythm of the indoor illumination level values, which follow the curve form of the window shade position fuzzy logic controller output. The LEDs fuzzy logic controller output signal effect reduction or increase of the LEDs average power output depending on the indoor illumination levels.

The designed lighting system should not be used with lighting intensity signal level values that lie outside the respective preset fuzzy logic controller membership function ranges.

4.8 Effect of Changing Shape of the Membership Functions

The objective of this test was to check and confirm if the system design control can be improved by changing the respective fuzzy logic controller membership function plot shape. The test was to compare and deduce which of the two shapes, triangular and trapezium, is most suitable for stability of the LED lighting system.

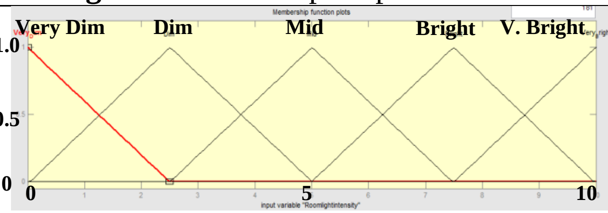
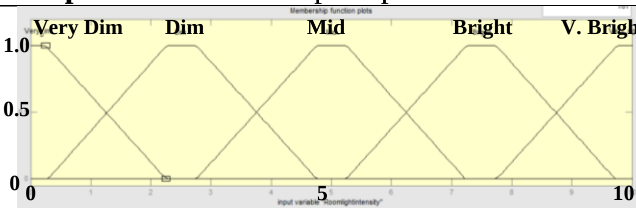
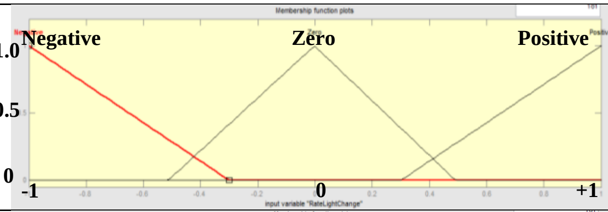
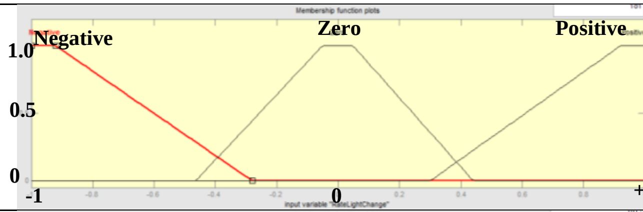
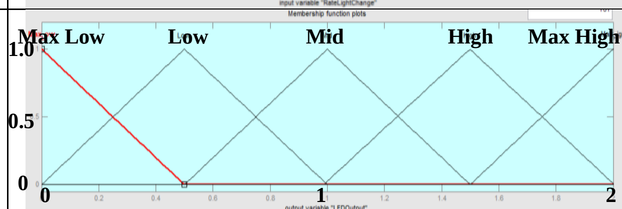
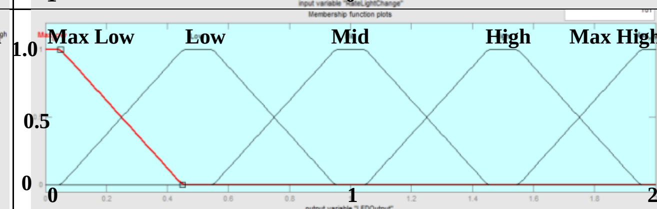
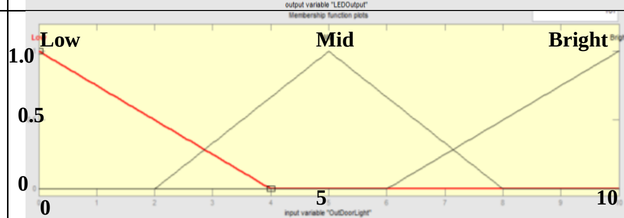
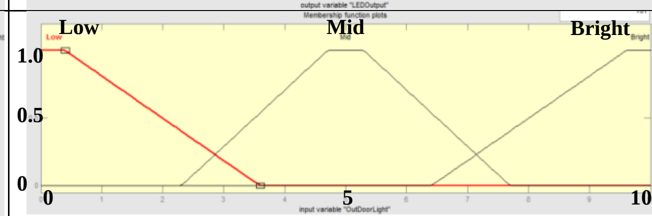
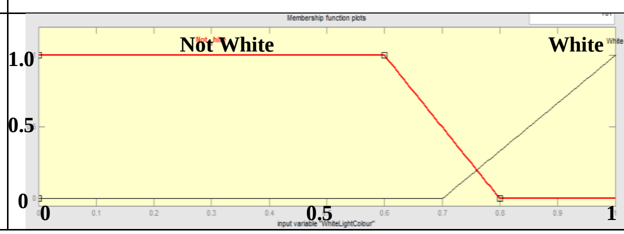
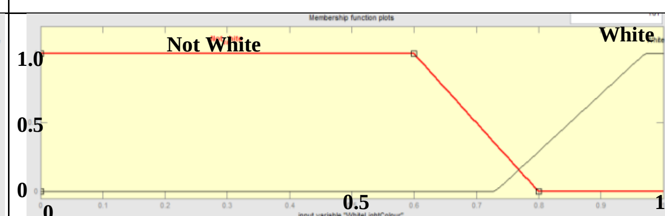
It was expected that the triangular shaped membership functions to be more stable due to their narrower top plot shape when compared with the trapezium shapes.

4.8.1 Results of testing effect of changing the plot shape of the fuzzy logic controllers' membership functions from triangular shape to trapezium shape.

The test was carried out using a 200Hz sinusoidal signal generator as the outdoor light intensity signal source. The other system parameters were maintained constant with the values for each red/green/blue input colour portion levels at 1, value of the window shade fuzzy logic controller output gain factor of 10, zero value for rate of change of the indoor light intensity, enabled room movement detector, and enabled room occupancy. The 200Hz sinusoidal signal amplitude was 10. The test result graph set 4.15 was used for comparing the wave forms of the outdoor light intensity signal, the window shade position controller output signal, indoor illumination level signal, and the LEDs fuzzy logic controller output signal. The first six rows of the table compare the shapes of the membership function plots for the window shade position and the LEDs' Fuzzy Logic controllers.

The results were obtained from the time based graphical representation of the simulation on various specific scopes of the MATLAB Simulink simulation model. The results are in waveforms of the various signals at specific monitoring points using the model scopes. The results are presented in form of screenshots. The waveforms are displayed in table for column-wise comparison purposes. Graph set 4.15 compares effect of changing the controller's membership function plot shapes from that of triangular to trapezium.

Graph set 4.15: Set of screenshots – Effect of changing from triangular to trapezium shapes of membership functions.

	Triangular membership shape	**Trapezium** membership shape
Membership function: Input- **Room light intensity**		
Membership function: Input- **Rate of change of room light intensity**		
Membership function: Output- **LEDs output**		
Membership function: Input- **Outdoor light intensity**		
Membership function: Input- **Colour product level**		

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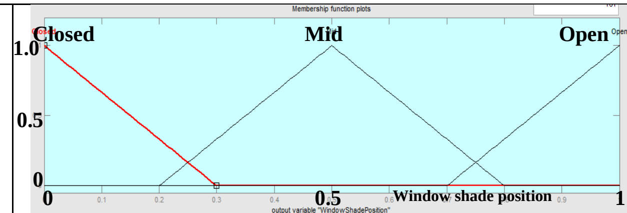
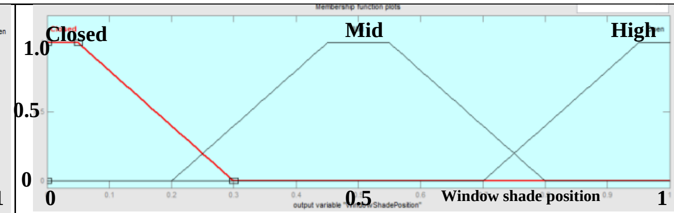
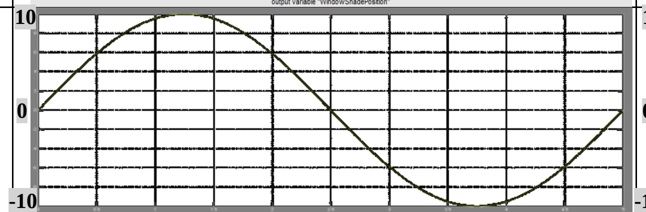
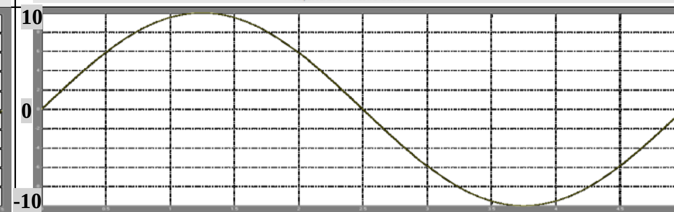
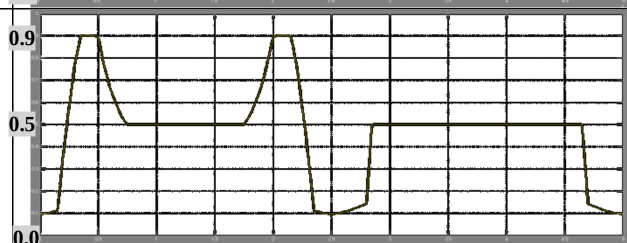
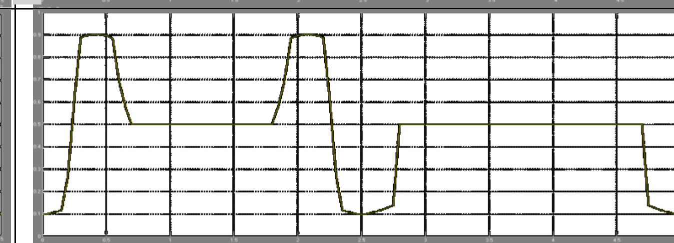
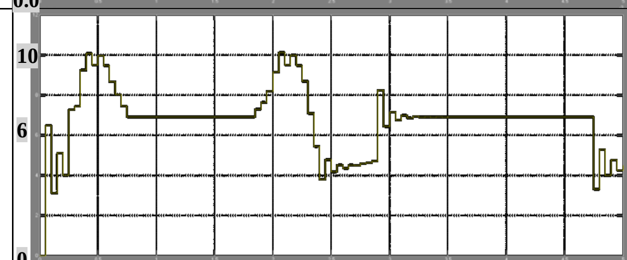
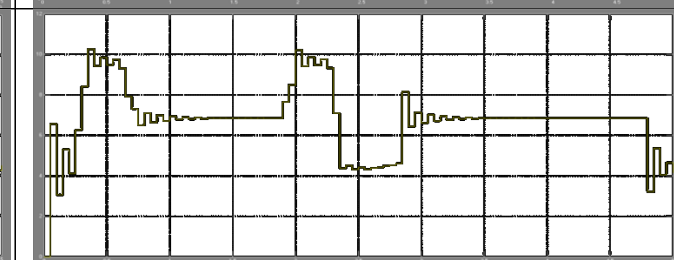
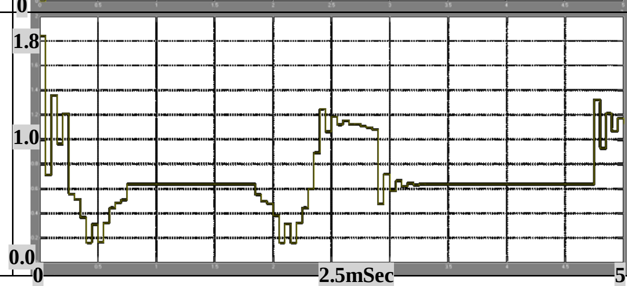
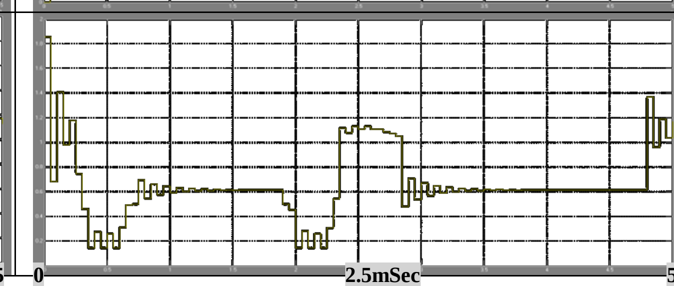
Membership function: Output- **Window shade position**		
Outdoor light - Input signal. Amplitude =10		
Window shade position fuzzy logic controller output		
Indoor (room) light level		
LEDs light level fuzzy logic controller output		

The wave forms displayed in graph set 4.15, where sinusoidal signal with amplitude of 10 is used for the outdoor light intensity, show that the window shade position controller output signal is low at low outdoor light input signal and rises to maximum value of 0.9 as the outdoor light signal passes through the 4 to 6 level values then falls to mid position value of 0.5 for any other values of outdoor light intensity beyond 9. It is observed that the shapes of the two sets of wave forms are similar. However, the duration at which the window shade position controller output signal is at maximum is longer in the trapezium membership function than with triangular shape. Another noted difference in the two sets is the oscillation transient duration of the indoor illumination levels and the LEDs' controller output signal. The triangular membership function set of output signal transient oscillations settle faster than those by the trapezium membership functions.

4.8.2 Discussion on effect of changing the plot shape of the fuzzy logic controllers' membership functions from triangular shape to trapezium shape.

The objective of this test was fully met. The system design control can be improved by changing the respective fuzzy logic controller membership function plot shape. The test confirmed that the narrower tipped membership function plot are more stable and more accurate than their counterparts with flat tops. Triangular shaped membership functions are better than trapezium ones for stable fuzzy logic control systems.

4.9 Effect of Shifting Plot Position of the Mid Membership Functions.

The objective of this test was to check and confirm if shifting the plot position of the mid membership function of the fuzzy logic controllers, the system settles in new values.

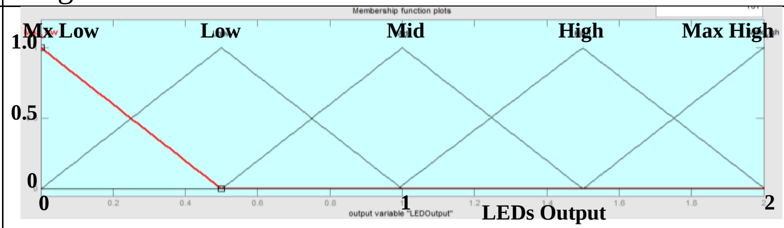
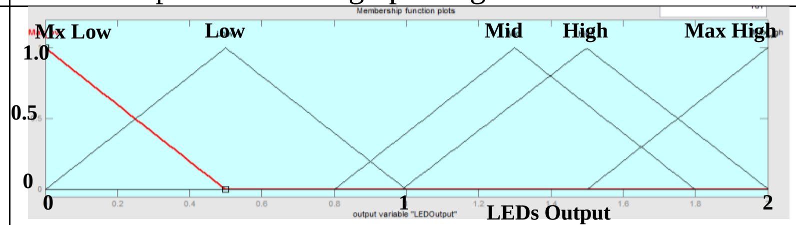
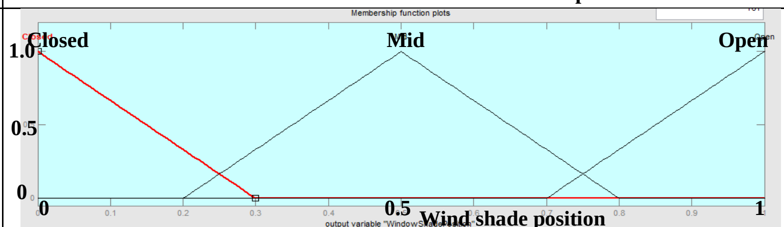
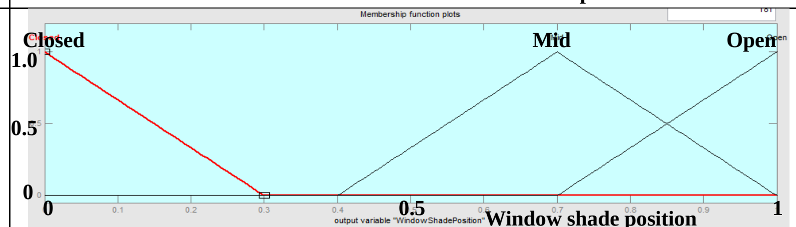
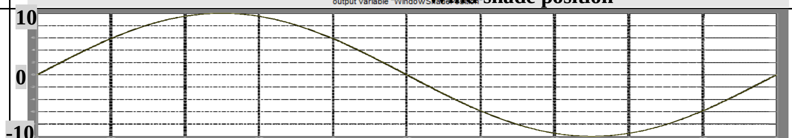
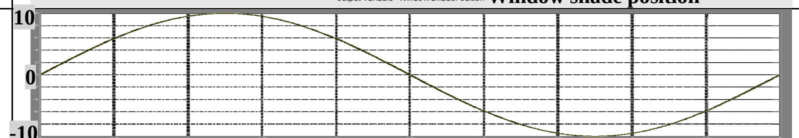
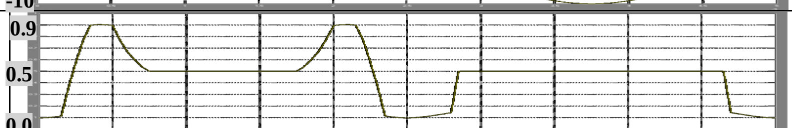
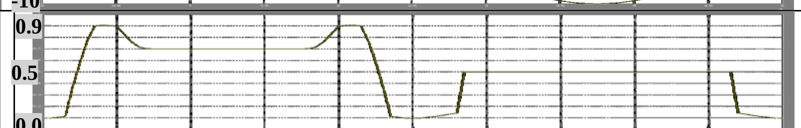
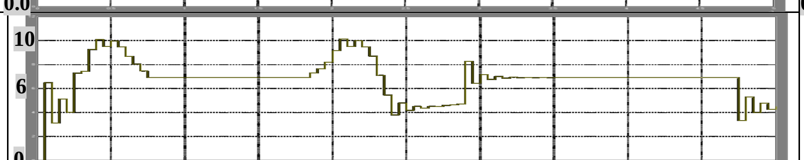
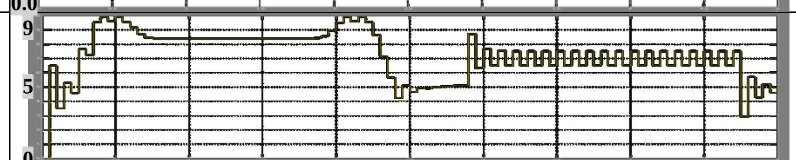
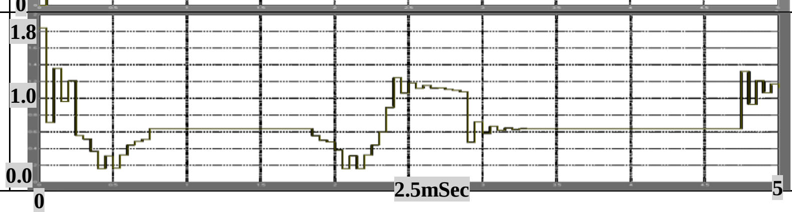
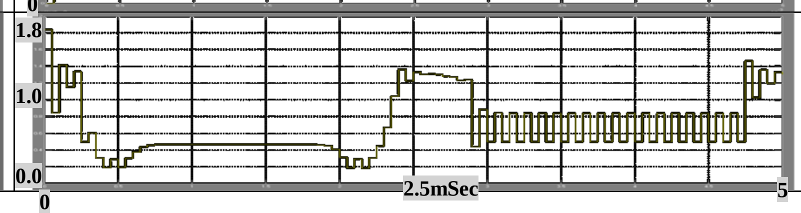
It was expected that when the mid membership function plot for the window shade position fuzzy logic controller is shifted to higher value in the scale range, the controller output signal also settles in a higher value level.

4.9.1 Results of testing effect of shifting position of the outputs' mid membership functions for the fuzzy logic controllers.

The test was carried out using a 200Hz sinusoidal signal generator as the outdoor light intensity signal source. The other system parameters were maintained constant with the values for each red/green/blue input colour portion levels at 1, value of the window shade fuzzy logic controller output gain factor of 10, zero value for rate of change of the indoor light intensity, enabled room movement detector, and enabled room occupancy. The 200Hz sinusoidal signal amplitude was 10. The test result graph set 4.16 was used for comparing the wave forms of the outdoor light intensity signal, the window shade position controller output signal, indoor illumination level signal, and the LEDs fuzzy logic controller output signal. The first two rows of the table compare the positions of the outputs' mid membership functions for the window shade position and the LEDs' Fuzzy Logic controllers.

The results were obtained from the time based graphical representation of the simulation on various specific scopes of the MATLAB Simulink simulation model. The results are in waveforms of the various signals at specific monitoring points using the model scopes. The results are presented in form of screenshots. The waveforms are displayed in table for column-wise comparison purposes. Graph set 4.16 compares effect of shifting the outputs' mid membership function for both fuzzy logic controllers.

Graph set 4.16: Set of screenshots – Effect of shifting the fuzzy controller output middle membership function plots.

	Mid membership function plot **in middle** of the graph range	**Mid** membership function plot **shifted to right hand-side** of middle position of the graph range
Membership function: Output- LEDs output level		
Membership function: Output- Window shade position		
Outdoor light - Input signal. Amplitude =10		
Window shade position fuzzy logic controller output		
Indoor (room) light level		
LED light level fuzzy logic controller output		

The waveforms displayed in graph set 4.16, where sinusoidal signal with amplitude of 10 is used for the outdoor light intensity, show that the window shade position controller output signal is lowest at low outdoor light input signal for both cases. The window shade position controller output signal rises to maximum value of 0.9 as the outdoor light signal passes through the 4 to 6 level values then falls to mid position value of 0.5, for case mid in middle, but 0.7 for case mid shifted to right hand side. It is observed that the shape of the two sets of wave forms are similar, apart from the higher values of the window shade position controller output and the indoor illumination level values when the outdoor light intensity is at high values, from 8 to 10. The LEDs' controller output signal, when the mid is shifted, is noted to be also at lower level in response to the indoor illumination values.

Shifting the fuzzy logic controller output mid membership function from middle of the plot to right hand-side has the effect of shifting higher the value of the settled indoor illumination level.

4.9.2 Discussion on effect of shifting position of the outputs' mid membership functions for the fuzzy logic controllers.

As was expected, when the mid membership function plot for the window shade position fuzzy logic controller was shifted to higher value in the scale range, the controller output signal settles in a higher value level.

This test confirmed that shifting the plot position of the mid membership function of fuzzy logic controllers the system control signals settle in new value levels. Controlling the window shade position and the LEDs output light to provide the desired room illumination levels could also be achieved through shifting the positions of the specific membership functions for each respective fuzzy logic controllers. Shifting the positions of the membership functions is a one method for fine tuning the designed lighting system controls.

CHAPTER 5- CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The study was set out to explore and design an intelligent lighting system based on fuzzy logic controller that uses multi-colour LEDs to produce light of the required luminance level and appropriate colour in a typical room space considering energy efficiency requirements. This study was based on the necessity to optimize utilization of the new generation of LEDs and the natural daylight in both homes and work places as a strategy to save lighting related energy costs, and at the same time improve comfort of living and working in such places. The study sought to answer these questions:

1. How can the output of an outdoor lighting level sensor be configured and processed to automatically control a room's window shade position?
2. How can the output of an indoor lighting level sensor be configured and processed to intelligently control LEDs' luminance and maintain the required room's illumination levels?
3. How can the output of an occupant detector that counts the number persons in a room be configured and processed to dim off the LEDs lights if the room is not occupied?
4. How can the output of a movement detector be configured and processed to dim off the LEDs if a movement in the room is not detected?
5. How can the output of a colour decoder/sensor be processed to accurately determine the multi-colour LEDs' output light colour and at the same time close the room's window shades if the output light is not white?
6. Can the integrated system of addressable sensors, window shade, fuzzy logic controllers, and multi-colour LEDs provide a typical room with light of appropriate colour at required intensity levels and still be efficient in electrical energy usage?

The empirical findings of the study are synthesized and explained in this chapter. Also explained in this chapter is the theoretical implication of the study and the recommendations for future works.

5.2 Empirical Findings

This section will synthesize the empirical findings to answer the study's research questions.

1. How can the output of an outdoor lighting level sensor be configured and processed to automatically control a room's window shade position?

In chapter 4 section 4.4, on effects of outdoor light intensity, the window shade position controller output signal smoothly rise from low values to high values, then lowers to mid values. It was also noted that there are three flat sections on widow shade controller output graphs; the window shade closed position with output value of about 0.18, the fully open position with output value of about 0.9, and the mid open position with output value of about 0.7. This confirmed that the window shade position fuzzy logic controller was operating in response to the fuzzy logic control table of operational rules. The room's window shade position could automatically remain closed for low outdoor light levels and open to maximum position once the outdoor light levels start rising, then close to middle position when the outdoor daylight is very bright.

The outdoor lighting level signal, through the Fuzzy Logic Controller, automatically controlled the room's window shade opening position in a manner similar to human reasoning basing it controllability on the "IF-THEN" control rules. The lighting system design was able to automatically harvest daylight to suit the desired room illumination level requirements.

The simulation model demonstrated how a fuzzy logic controller can be used to process an outdoor light level signal and control a typical room's window shade position, heuristically harvesting daylight for energy efficient illumination of the room.

2. How can the output of an indoor lighting level sensor be configured and processed to intelligently control LEDs' luminance and maintain the required room's illumination levels?

Section 4.2 of chapter 4 on effects of the rate of change of the indoor light intensity, the indoor light level sensor output signal is demonstrated to affect the LED's current pulse width via the fuzzy logic controller. The results also confirm that room illuminance level stability is affected by the way the indoor light sensor signal is configured for use in the LEDs fuzzy logic controller. However, the system stability does not depend on magnitude of the rate of change signal but on some critical values of the rate of change. The system is seen to be stable even without input from the rate of change of the indoor illumination levels. This does not mean that the signal for rate of change of the indoor light intensity is not required, but it implies that the fuzzy logic controller settings require tuning.

The room's illumination was maintained above a certain level irrespective of absence of the outdoor light contribution. The LEDs' output light depends on illumination levels in the room and configuration of its fuzzy logic membership functions. When there is no outdoor light, the room is illuminated by the LEDs only. When the outdoor light into the room is high enough to the required levels, the LEDs' output luminance is at the lowest level possible, thus saving on electric energy. However, the simulation results showed that the lowest level of the LEDs output light is not zero as expected. This problem was associated with fuzzy logics' weakness of approximation. Lowest value of the fuzzy logic controller output is not zero but a number with approximate value of zero.

The simulation model design proved that an indoor light intensity level sensor signal could be processed through a fuzzy logic controller to intelligently control a room's LEDs light intensity and maintain the required illumination levels.

3. How can the output of an occupant detector that counts the number persons in a room be configured and processed to dim off the LEDs lights if the room is not occupied? Also, how can the output of a movement detector be configured and processed to dim off the LEDs if a movement in the room is not detected?

The simulation model design tests, in chapter 4 section 4.6 on cause and effect of absence of colour decoder, movement detector, and room occupancy signals, demonstrated that the lighting system LEDs could be dimmed off by a signal from either the room occupancy counter, or the movement detector, or the colour decoder. The system model incorporated three enabler signal switches at the output of the LEDs fuzzy logic controller. However, the use of enabler switch for zero value colour decoder signal was found to cause disruption in the system signal flow. The simulation model did not require colour decoder signal enabler switch because the same zero value signal is duplicated after the multiplier blocks.

4. How can the output of a colour decoder/sensor be processed to accurately determine the multi-colour LEDs' output light colour and at the same time close the room's window shades if the output light is not white?

Chapter 4 section 4.5 on effects of different level values of colour portions, the system was found able to calculate the respective primary colour portion signal level ratios, which are used apportioning the average power for each respective red, green, and blue colour LED. The model simulated how the calculated colour portion ratios could be used to differentiate a white light from coloured one and then close the room's window shades if required light is not white. The model design demonstrated how an output of a colour sensor (colour decoder) with three distinct signal lines, for each specific primary colour, can be processed to accurately determine a multi-colour LEDs' lamp output light colour.

5. Can the integrated system of addressable digital sensors, window shade, fuzzy logic controllers, and multi-colour LEDs provide a typical room with light of appropriate colour at required intensity levels and still be efficient in electrical energy usage?

Section 4.7 on effect of too high, moderate, low and negative values of outdoor light signals, section 4.8 on effect of changing shape of the membership functions plots, and section 4.9 on effect of shifting position of the outputs' mid membership functions for the fuzzy logic controllers, illustrated that the appropriate window shade position for any daylight intensity level, and the LEDs' output luminance can easily be adjusted by simply shifting the position of the membership functions in the plots, or adding more sets of membership functions, or changing the shape, or doing a combination of the three. The lighting system operates well when the outdoor and indoor lighting signal level values are within the respective fuzzy logic controller membership function set range. If the input signal values are outside the membership function range, the controller output signal is fixed in the mid-range and is invariant to the input changes.

The lighting system is more stable and sensitive to signal inputs if the fuzzy logic controller member ship functions are of sharp-tipped shapes than those with flat topped shapes.

The research simulation model fulfilled the main objective of designing an intelligent lighting system based on fuzzy logic controller that uses multi-colour LEDs to produce light of the required luminance and appropriate colour in a room space that considers energy efficiency requirements. The integrated system of digital sensors, fuzzy logic controllers, and the multi-colour LEDs is energy efficient and intelligent, ensuring that the electric energy for the LEDs is used only when the outdoor daylight is not required and only when the room is occupied and the user is not asleep. The lighting system is sensitive to colour needs; the window shade closes when the room's required light colour is not white.

5.3 Theoretical Implication

The theoretical cases for lighting systems with fuzzy logic controllers need to be revisited in order to further understand the dynamics of lighting systems and how to the designs can be made more beneficial to mankind.

In a paper by S.D. Panjaitan [1], fuzzy logic scheme is proposed as a basis to control lighting system in building zone where the fluorescent lamps are the controlled objects. The proposed lighting design procedure determines the maximum number of lamps that should be used according to the room function. Then the proposed controller is activated and deactivated according to information from occupancy sensors, which gives information about room occupancy. This method saves electrical energy for lighting, but may not be most appropriate for a small room which has a few number of lighting lamps.

The paper by M.A.A. Saleh [29] also describes a fuzzy controller that controls the number of lamps lit using the number of people inside the room and the required illuminance as control inputs. This method also is capable of reducing the electrical energy, but not suitable for smaller rooms with only one or two lamps.

M. T. Lah [18] proposed a modern approach to control the inside illuminance with fully automated fuzzy system for adjusting shades, which responds constantly to the changes in the available solar radiation, which makes decisions as it follows the human thinking process. The control algorithm contains a cascade control with fuzzy controller as the main and conventional PID-(proportional-integral-derivative) controller as auxiliary controller. This approach was very good for harvesting the daylight. This design was limited only to daylight harvesting but does not consider artificial lighting energy requirements.

The researched design lighting system with fuzzy logic controller operate in a manner similar to human reasoning. Fuzzy logic controllers are suitable for lighting systems due to the none-linearity of lighting brightness and different lighting requirements for different persons.

This research study proposes a design of lighting system which combines the use of the high efficacy LEDs, the daylight harvesting techniques, and production of coloured light for more comfort and convenience of the space user. The lighting system was designed with need for saving electric energy in mind. Of major concern in the design was reduction of human intervention in switching off or dimming the electric lamps. This reduced human intervention ensurs that energy saving is part of the lighting system. The system design considers the colour decoder to be of a flexible type which is sensitive to the room users' need for coloured light and the associated emotional soothing effects.

A fuzzy logic controller has been found be a system controller that is easily configured to operate automatically and in a manner similar to human reasoning, displaying artificial intelligence capabilities.

5.4 Recommendations for further research works

The research work was limited to computer model simulation, and therefore, further research works in implementing the system is recommended. The proposed physical implementation scheme may be used in realizing the multi-coloured lighting system.

The system need to be built up with real hardware and confirm control of the actual required room space illumination and test the desirable lighting colour. The fuzzy logic membership functions could be tuned-up to confirm functionality of the 'rate of change of the indoor light intensity' signal in stability of the lighting system. The colour decoder requires further checks for accuracy and suitability.

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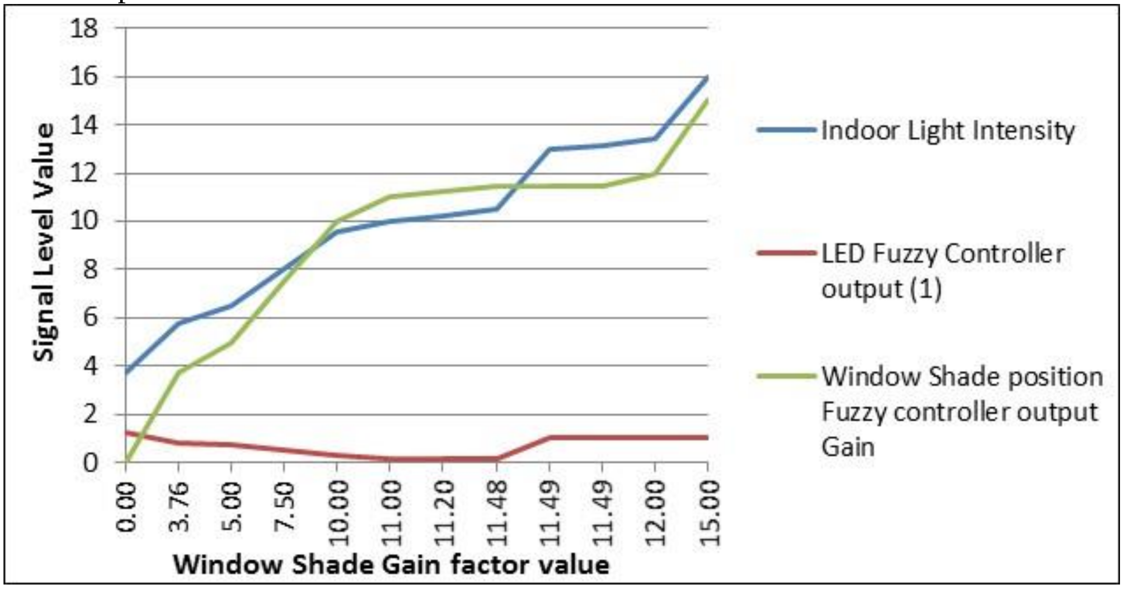
APPENDICES

Appendix 1: Effects of Window shade position Fuzzy logic Controller output gain factor

Table of data for window shade gain factor

	Window Shade position Fuzzy controller output Gain	**Indoor Light Intensity**	**LED Fuzzy Controller output (1)**
1	0.000	3.760	1.253
2	3.760	5.775	0.834
3	5.000	6.495	0.716
4	7.500	8.000	0.489
5	10.000	9.575	0.292
6	11.000	10.000	0.160
7	11.200	10.230	0.162
8	11.480	10.480	0.165
9	11.490	13.000	1.000
10	11.495	13.100	1.000
11	12.000	13.440	1.000
12	15.000	16.000	1.000

Line Graph

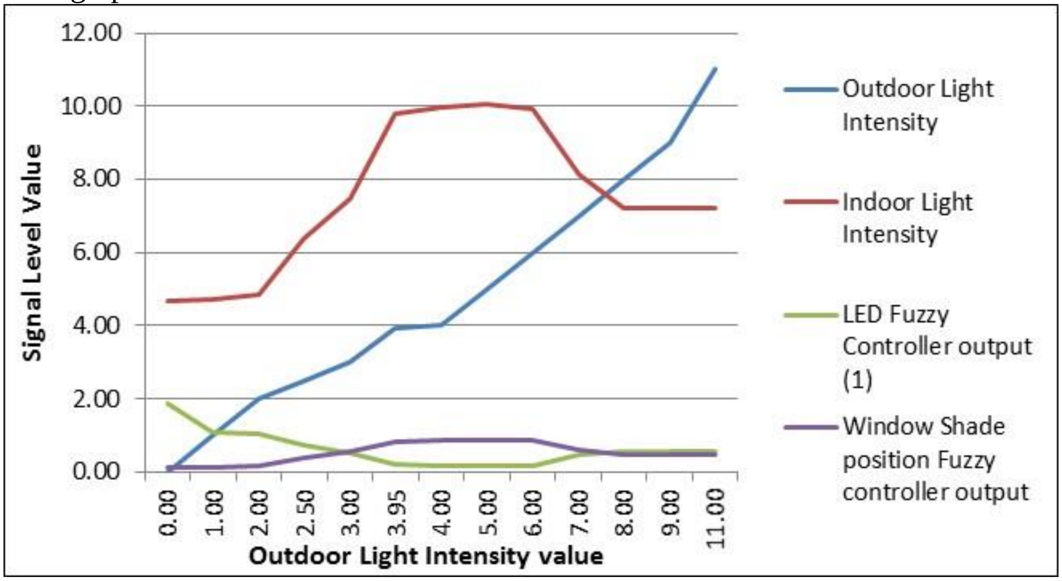


Appendix 2: Effects of outdoor light intensity

Table of data

	Outdoor Light Intensity	**Window Shade position Fuzzy controller output**	**Indoor Light Intensity**	**LED Fuzzy Controller output (1)**
1	0.00	0.130	4.680	1.870
2	1.00	0.138	4.735	1.076
3	2.00	0.152	4.838	1.053
4	2.50	0.380	6.400	0.730
5	3.00	0.550	7.458	0.505
6	3.95	0.839	9.800	0.20
7	4.00	0.859	9.950	0.170
8	5.00	0.870	10.050	0.160
9	6.00	0.857	9.940	0.170
10	7.00	0.608	8.113	0.483
11	8.00	0.500	7.220	0.573
12	9.00	0.500	7.2198	0.573
13	11.00	0.500	7.2193	0.573
14	12.00	0.500	7.220	0.574

Line graph

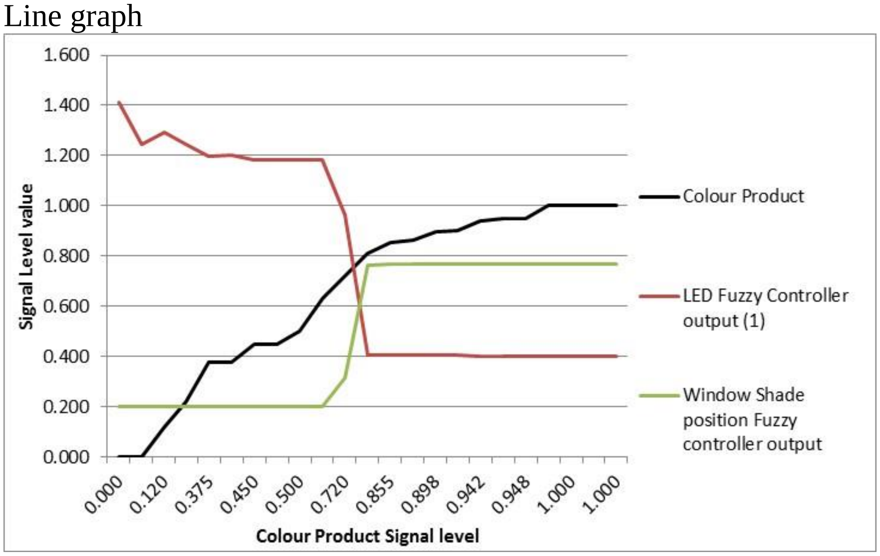


Appendix 3: Effects of Colour Product (product of the primary colour's ratios)

Table of data

	Colour Product	LED Fuzzy Controller output (1)	Window Shade position Fuzzy controller output
1	0.000	1.412	0.2000
2	0.000	1.2428	0.2004
3	0.120	1.2934	0.2004
4	0.222	1.2429	0.2004
5	0.375	1.1991	0.2004
6	0.375	1.2000	0.2004
7	0.450	1.1850	0.2004
8	0.450	1.1850	0.2004
9	0.500	1.1852	0.2004
10	0.630	1.1852	0.2004
11	0.720	0.9658	0.3150
12	0.810	0.4080	0.7650
13	0.855	0.4060	0.7681
14	0.862	0.4055	0.7680
15	0.898	0.4040	0.7681
16	0.903	0.4038	0.7680
17	0.942	0.4021	0.7681
18	0.947	0.40155	0.7681
19	0.948	0.40155	0.7681
20	1.000	0.40155	0.7681
21	1.000	0.40155	0.7681

Line graph



Appendix 4: Effects of different portion level values of the primary colours

Table of data

	Red Colour Portion	**Green Colour Portion**	**Blue Colour Portion**	**Colour Product signal**	**LED Red colour signal**	**LED Green colour signal**	**LED Blue colour signal**
1	1	0	0	0.00	0.412	-1	-1
2	1	1	0	0.00	0.2428	0.2428	-1
3	1	0.3	0.4	0.12	0.2934	-0.612	-0.483
4	3	2	1	0.22	0.243	-0.1715	-0.5857
5	0.5	0.75	1	0.38	-0.4005	-0.1007	0.2
6	1	0.75	0.5	0.38	0.2	-0.101	-0.4004
7	0.5	0.9	1	0.45	-0.4074	0.0667	0.1852
8	1	0.9	0.5	0.45	0.1852	0.0667	-0.4074
9	1	1	0.5	0.50	0.185	0.185	-0.408
10	1	0.9	0.7	0.63	0.1854	0.0667	-0.1703
11	1	0.9	0.8	0.72	-0.325	-0.1295	-0.2262
12	1	0.9	0.9	0.81	-0.592	-0.328	-0.633
13	1	0.95	0.9	0.86	-0.95	-0.6143	-0.6345
14	2	1.9	2.1	0.86	-0.614	-0.632	-0.5945
15	0.9	0.95	0.9	0.90	-0.6174	-0.5952	-0.6175
16	1	0.95	0.95	0.90	-0.596	-0.616	-0.6164
17	0.8	0.85	0.85	0.94	-0.6216	-0.5979	-0.5979
18	0.95	0.95	0.9	0.95	-0.5982	-0.5985	-0.6193
19	0.9	0.95	0.95	0.95	-0.6174	-0.5982	-0.5982

Line graph