Intelligent Lighting System Design With Fuzzy Logic Controller

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Abstract
This paper describes a design of an intelligent energy efficient lighting system based on fuzzy logic controller that uses white LEDs to produce light at the required luminance level in a typical room space. The lighting system incorporates automatic control of a room's window shade opening, conveniently harvesting daylight.
The study contains the simulation of the design in a MATLAB software environment using Fuzzy Logic Toolbox and Simulink blocks.
The model test results demonstrate that the LEDs' output average power automatically reduces as daylight entering the room increases. The designed lighting system intelligently optimizes on the high efficacy LEDs and the natural daylight in illuminating a room to required levels.Electrical energy for lighting the room is used only when the room is occupied and the artificial lighting is required.

Keywords
Fuzzy Logic Controller, Membership Function, Artificial Intelligence, Lighting Control, Daylight Harvesting

I. Introduction

Since the discovery and use of incandescent electric lamps by end of 19th century, lighting systems have undergone many major developments. Lighting can account for up to 20% of a household's yearly electricity usage, and up to 40% a year in commercial buildings [4-5].Research focusing on more efficient lighting systems is an on-going exercise driven by the need to save energy.The use of control technology in electric light dimming, daylight harvesting, and movement detection can greatly improve lighting energy efficiency [5][10].
The current generations of light emitting diodes (LEDs) are more efficient, some having efficacies of more than 100 lm/w [7][8][10][12]. The LED characterized by mercury-free, high efficiency, and long life cycle is expected to be the new generation of light source [1][12].
Most past papers on control of lighting in a room using Fuzzy logic controllers, deal with switching on or off a number of lighting lamps [1][6]. Other papers use fuzzy logic controllers for dimming incandescent lamps [2] and controlling homogeneity of light intensity from LED lamps [11]. Other papers have shown use of Fuzzy logic controllers in daylight harvesting [9]. There is very little literature for design research on control of LED lighting using Fuzzy logic.
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. The main objective of this study was to design an intelligent lighting system based on fuzzy logic controller that uses white LEDs to produce light of the required luminance level in a room space considering energy efficiency requirements. The study combines the benefits of daylight harvesting techniques and artificial intelligence techniques of using fuzzy logic principles in automatic control of amount light from the modern high efficient LEDs.
The comfortable brightness level in a room is a range which could conveniently be controlled using fuzzy logic controllers. The basic concept underlying fuzzy logic is that of a linguistic variable, that is, a variable whose values are words, such as dim, bright, very bright, etc, rather than numbers. Fuzzy logic is a very powerful tool for dealing quickly and efficiently with imprecision and non-linearity issues requiring decision making.
This study is adesign and simulation of the lighting system using Simulink software blocks in MATLAB environment. However, a physical implementation scheme for the lighting system, using appropriate microcontrollers and addressable digital sensors, was also researched and proposed for future work.

II. Materials and Methodology

A. Production of LED light

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 (scale) [3]. For this reason a driver circuit is designed essentially to drive LEDs at the required constant current. This is best carried out using low frequency constant amplitude current pulses. Fig. 2.1 is a circuit diagram demonstrating a LED's PWM controlled driver. A pulse controlled switch chops DC power to the LED. Fig. 2.2 is the theoretical waveform of the PWM generator output signal, the voltage (V_R) across the LED, and its current (V_R/R).
A chopped dc voltage is produced in the LED resistor terminal as follows:
$V_R = T_{ON}/(T_{ON} + T_{OFF})V_s = T_{ON}/T\ V_s = \alpha V_s$ (2-1)
Where $T = T_{ON} + T_{OFF}$ = chopping period.
$\alpha = T_{ON}/T$ = duty cycle (duty ratio)
RMS value of output voltage
$V_{or} = [\alpha V_s^2]^{1/2} = \sqrt{\alpha}\ V_s$ (2-2)
RMS value of output current
$I_{or} = [\alpha(V_s/R)^2]^{1/2} = \sqrt{\alpha}\ (V_s/R)$ (2-3)
Power delivered to the LED
$PLED = I_{or}V_{or} = \sqrt{\alpha}(V_s/R)\sqrt{\alpha}V_s = \alpha\ (V_s^2/R)$ (2-4)
Hence, $PLED = K\alpha$ (2-5)
Where K is a constant, (V_s^2/R), as long as the dc source, V_s, is maintained constant.

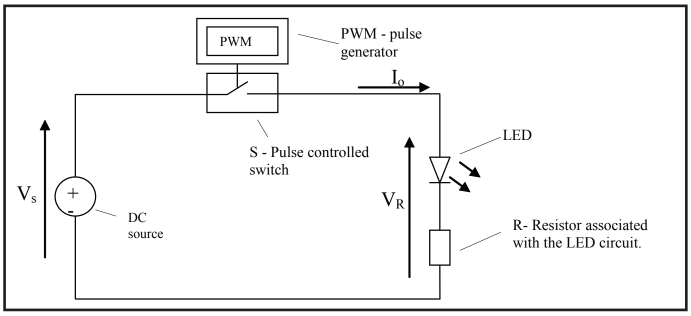

Fig. 2.1: Circuit Diagram PWM Controlled LED Driver

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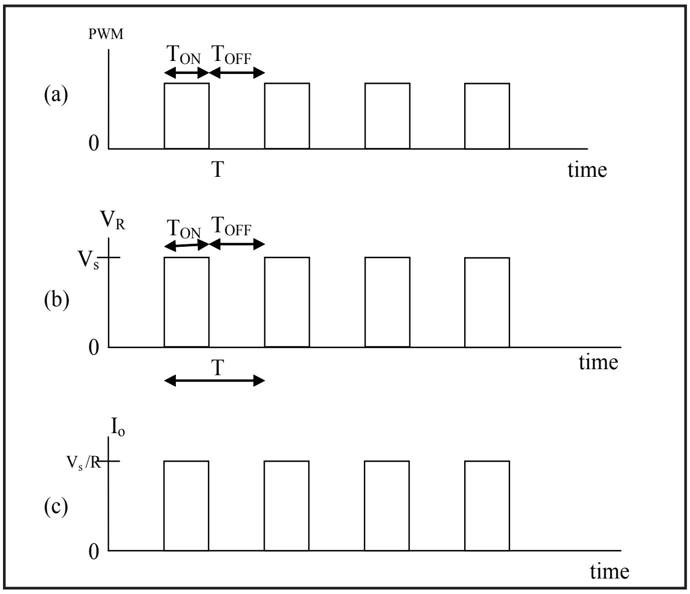


Fig. 2.2: Theoretical Waveforms for the Driver Pulses

The average LED current (average power) is controlled by varying the duty cycle (α) of the PWM pulse generator.

B. Existing Methods of Controlling LEDs Output Light

Duty cycle (α) of the pulses is controlled through amplitude of the PWM generator reference signal (input to the PWM generator). Most PWM generators require an input signal whose value level could be controlled from 0 to 1.

There are three main methods for controlling duty cycle for a LED driver to effect appropriate light dimming -

1. Discrete Timed Signal Value Levels – Time Programmed Operation

The controlling signal value for the LEDs driver pulse generator is constant for a set period of time after which it changes to another value level.

2. Discrete Signal Value Levels – Manual Operation

The controlling signal value for the LEDs pulse generator is constant and it remains so until a manual intervention is introduced and moves the signal value to another level.

3. Continuous Signal Value Levels - Intelligent and Sensor operated

The controlling signal value for the LEDs driver pulse generator is not constant but keeps on varying in response to another signal from an appropriate environmental sensor.

The intelligent and sensor operated control signal method was chosen because of its ability to automate dimming of the LEDs output light without human intervention. This method of automatic signal control is most suitable with Fuzzy Logic controllers.

C. 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 because of its generalization of light level settings, simplicity and auto-control.

A basic configuration of a two input fuzzy logic controller is illustrated in fig. 2.3. 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 for a PWM pulse generator.

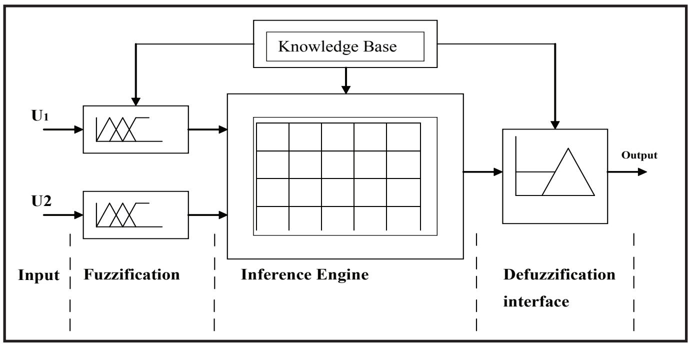


Fig. 2.3: Illustration Diagram for Fuzzy Logic Controller

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 rule set.

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, using a membership function, into non-fuzzy (definite or crisp) control action signal.

The operation of the fuzzy logic controller is based on a set decision making control rules, fuzzy "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 (2-6)

For k =1, 2, 3… n.

Where:-

- R_k is the kth 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 kth antecedent pairs and consequent pair respectively;
- n is the number of rules.

D. Typical Room Space and Lighting Control Design

The figure 2.4 shows a typical room whose inside illumination level is controlled by light from a set of ceiling mounted LED lamps and outdoor daylight through clear-glass window with electrically movable shades (light blinders). It is assumed that the number and the rating of the 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.

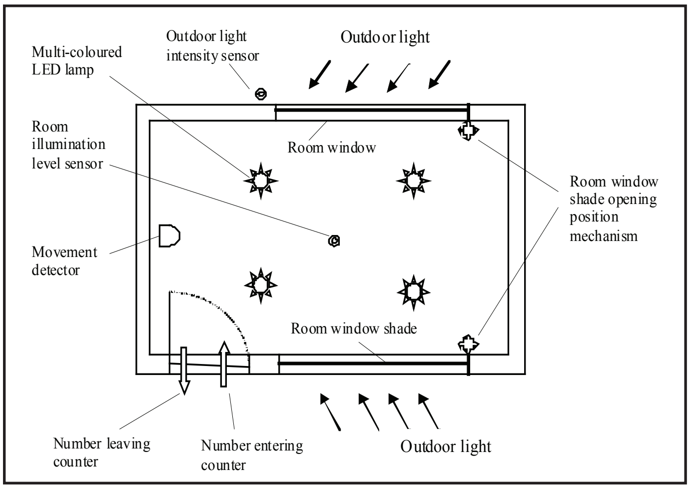


Fig. 2.4: Typical Room Diagram With Controlled Light

Fig. 2.5 shows basic scheme of the 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 from the LEDs.

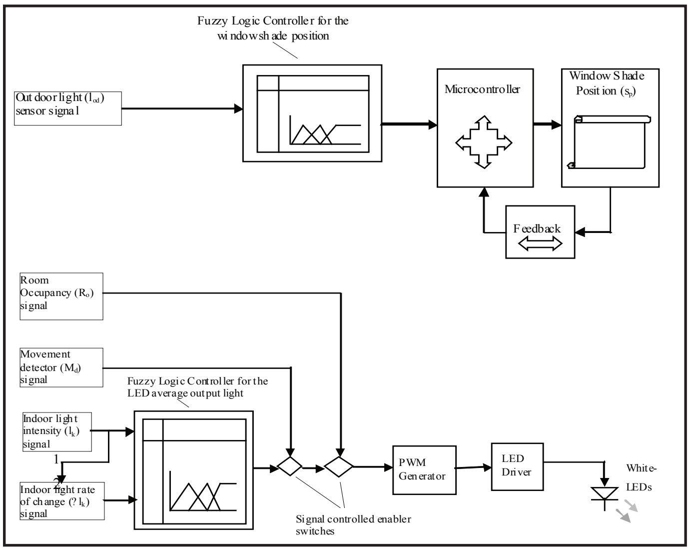


Fig. 2.5: Basic Scheme for the Room Lighting Control

E. The Window Shade Position Fuzzy Logic Controller

The one input to the window shade opening (position) fuzzy logic controller is outdoor light intensity level signal (L_{od}).

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

Fig.2.6 shows the required membership function (fuzzy logic graph) 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.

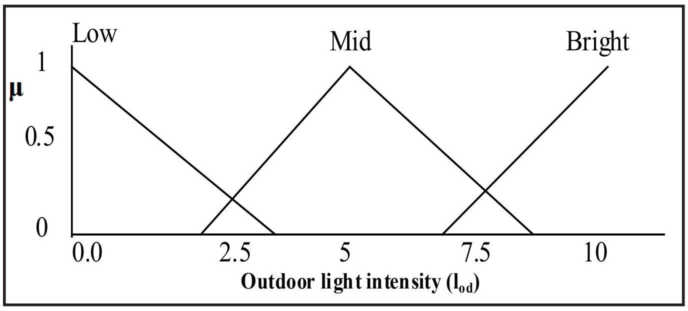


Fig. 2.6: Outdoor Light Level Input – Membership Function

Fig. 2.7 shows the window shade position fuzzy logic controller output membership function algorithm plot for defuzzification of the output, P_r,. The output position reference scale is 0 to 1, with 0 for fully closed and 1 for fully open window shade position.

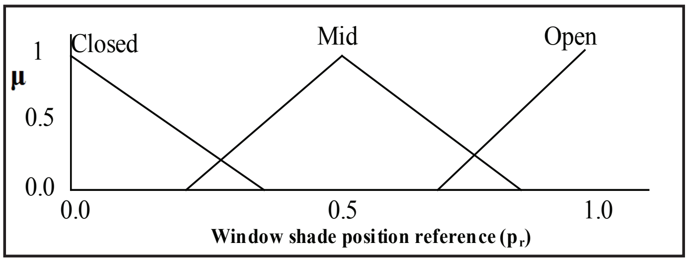


Fig. 2.7: Window Shade - Output – Membership Function

Table 2.1: Window Shade Position Output Fuzzy Control Rules

Outdoor light (l_{od})	Low	Mid	High
Shade position state	Closed	Open	Mid

F. The LEDs' Output Fuzzy Logic Controller

Fig. 2.8 is the membership function algorithm plot for the room light intensity/level where the universe of discourse ranges from 0 to 10.

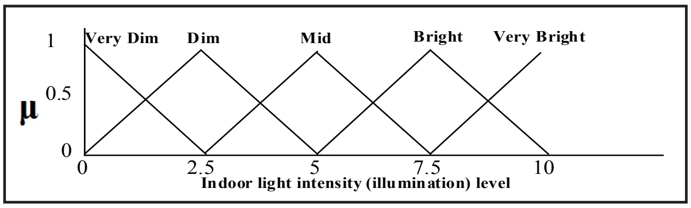


Fig. 2.8: Indoor Light – Input Membership Function

Fig. 2.9 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.

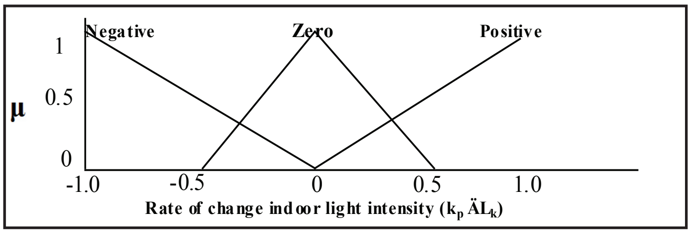


Fig. 2.9: Rate of Change of Light – Membership Function

Fig. 2.10 is the membership function algorithm plot for output of the LEDs' output light level fuzzy logic controller. The universe of discourse range was from 0 to 2.

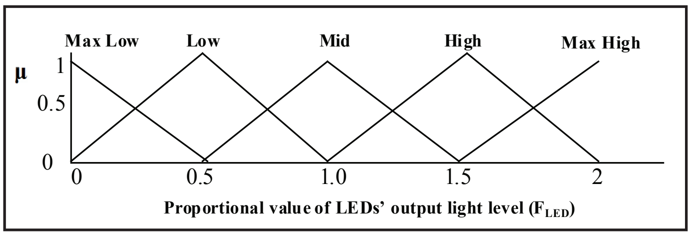


Fig. 2.10: LEDs' light – Output Membership Function

Table 2.2 shows a matrix of rules for controlling the LEDs average power output using the indoor light level L_k and its rate of change ΔL_k

Table 2.2: LEDs Output Fuzzy Control Rules

Room light \ Rate of change	Negative	Zero	Positive
Very Dim	Max High	Max High	High
Dim	Max High	High	Mid
Mid	High	Mid	Low
Bright	Mid	Low	Max Low
Very Bright	Low	Max Low	Max Low

G. Simulation Model Scheme

The lighting system software model was assembled and tested using the Simulink blocks ina Simulink environment. Fig. 2.11 is a screenshot showing the configured and block-assembled simulation model onSimulink platform.

Algorithms for the fuzzy logic controllers are in form of membership function plots and control rulesconfigured using the Fuzzy LogicToolbox.

The simulation was based on assumption that the daylight contribution to the indoor light (room illumination) is directly proportional to the window shade opening position. That is, the outdoor light to the room (L_{od}) is equal to constant (k_{od}) times the window shade position control signal (pr), as equation (2-7)

$$L_{od} = k_{od}p_r \qquad (2\text{-}7)$$

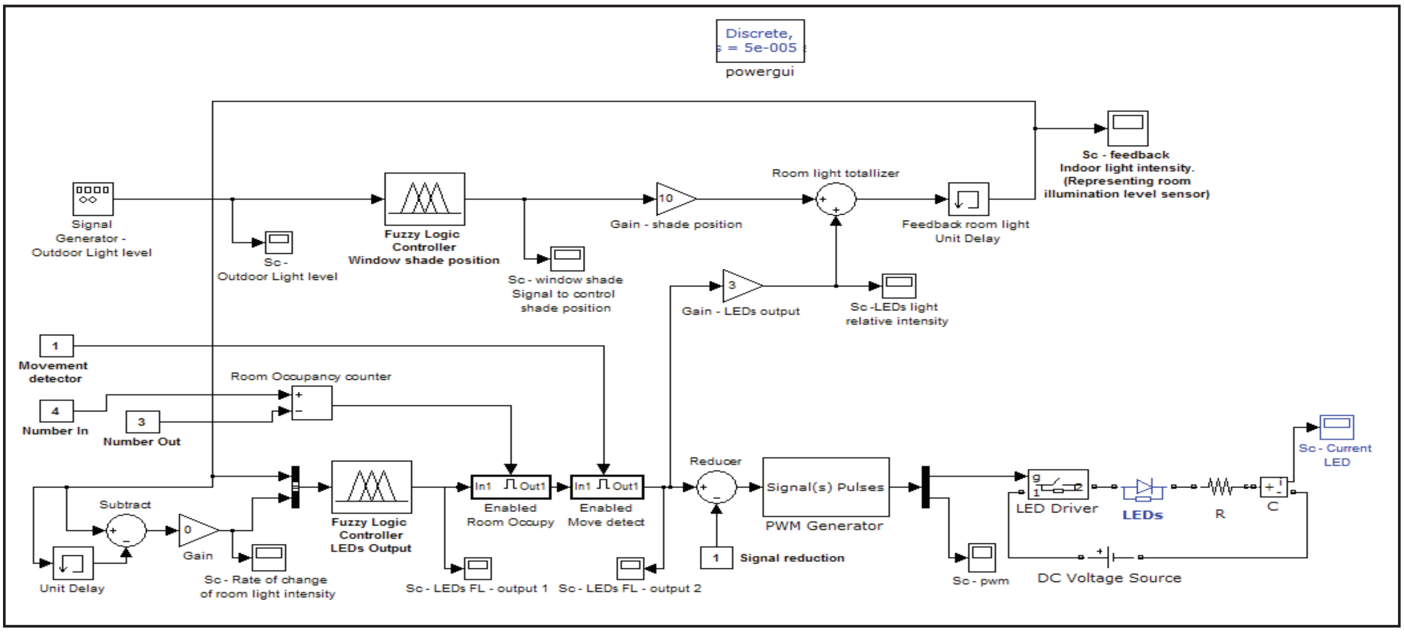


Fig. 2.11: Screen Shot of Simulation Scheme

The LEDs' light output (L_{LED}) is equal to constant (k_{LED}) multiplied by the signal from the LEDs fuzzy controller output (F_{pwm}) that control the PWM generator as shown by equation (2-8).

$$L_{LED} = k_{LED}F_{pwm} \qquad (2\text{-}8)$$

The room illumination level (R_i) is equal to sum of both outdoor light and the LEDs output as shown in equation (2-9).

$$R_i = k_{od}p_r + k_{LED}F_{pwm} \qquad (2\text{-}9)$$

Indoor light signal feedback to the LEDs fuzzy logic controller (L_k) is shown in equation (2-10)), where z-1 is unit delay in sampling.

$$L_k = z^{-1}R_i = R_{i-1} \qquad (2\text{-}10)$$

Rate of change of indoor light (ΔL_k) is equal to room light intensity signal value (R_{i-1}) minus one simulation time delayed room light intensity value (R_{i-2}), as shown in equation (2-11).

$$\Delta L_k = R_{i-1} - R_{i-2} \qquad (2\text{-}11)$$

The simulation was carried out by using a preset sinusoidal signal generator as outdoor light sensor. A manual input of constants was also used for the light sensor in testing effect of varying the outdoor light levels.

Both the movement detector and the room occupancy signals were also manually input. Signal levels for each part on the model were monitored by means of connected Simulink scope blocks.

H. Physical Implementation Schematic Diagram

Figure 2.12 shows a schematic of the proposed electronic devices for implementing the modeled lighting system.

All the devices are expected to intercommunicate through I2C bus. Any other appropriate digital communication protocol may also apply. The software for the Fuzzy Logic Controllers and signal flow programming would be installed in the master microcontroller.

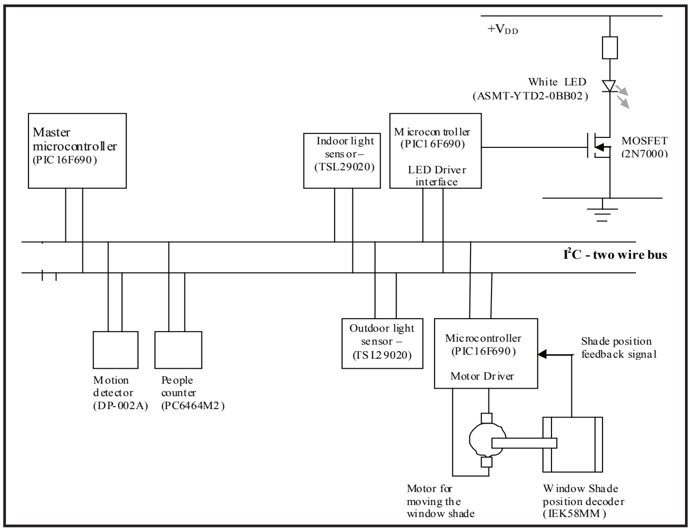


Fig. 2.12: Schematic Diagram for the System Implementation

III. Results and Discussion

Inputs to the simulation model were in form of constant values based on Simulink constant blocks specific for movement detector, number of persons entering room, and number of persons leaving room respectively. Also used as input is a sinusoidal signal generator for outdoor light sensor.

The simulation model outputs were monitored using the Simulink scope blocks each for window shade position fuzzy logic controller output, the indoor light intensity level feedback, the rate of change of the indoor light intensity, the LEDs output fuzzy logic controller output, and the LED currents respectively. Throughout the experiment, the simulation time was set at 0.005 seconds.

Effect of outdoor light intensity on indoor illumination levels and the LEDs' output.

The test results are shown in fig. 3.1 which is a line graph where the values of the outdoor light intensity are compared with the resulting values of the window shade position controller output, the indoor illumination levels, and the LEDs' fuzzy logic controller output.

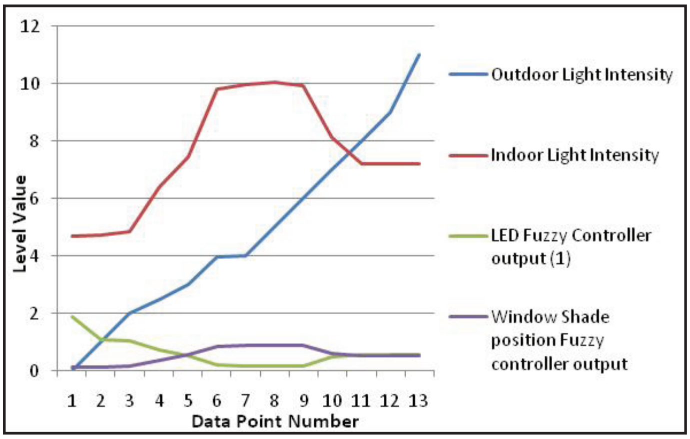


Fig. 3.1: Line Graph for Effect of Outdoor Light Intensity

Screen shots of the outdoor light intensity sinusoidal signal, the window shade controller output, the indoor light levels, the LEDs' fuzzy controller output signals, and the LED's current pulses waveforms are tabulated in fig 3.2. The line graphs in fig. 3.1 and the waveforms in fig. 3.2 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 control rules in table 2.1. At very low outdoor light intensity levels, less than value 2, the window shade opening signal is very low, 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 0.5.

At very low outdoor light intensity levels, less than value 2, the indoor illumination level values are lowest but the LEDs' fuzzy logic controller output signal is at highest, just as per the LEDs output fuzzy logic controller statement rules in table 2.2. The oscillation in the indoor light intensity wave forms is a caused by the LEDs' fuzzy controller trying to compensate for the varying indoor illumination levels. At middle levels of the outdoor light intensity, the indoor illumination level is highest, about 10, while the LEDs' controller output is lowest, at about 0.16.

The external (outdoor) light affects the opening room's window shade opening but not the LEDs' output lighting. However, the window shade opening determines intensity of light from the LEDs. The fuzzy logic controllers are configured to allow only enough light to the room; if the outdoor light intensity is too high (very bright) the window shade closes to half-way position.

The outdoor light intensity level automatically, but through the window shade opening, determines the output signal level of the LEDs' fuzzy logic controller. The more the window shade is opened, the lower the average power used by the LEDs.

Fig. 3.2 confirms that LED's current pulses are narrower where the window shade opening is high. Width of the pulses is directly proportional to the duty cycle (α) of the PWM pulse generator which is also proportional to the controller's output signal level. The pulse period is constant at 0.25ms.

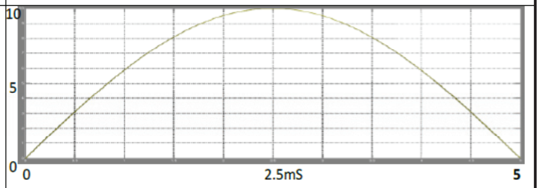
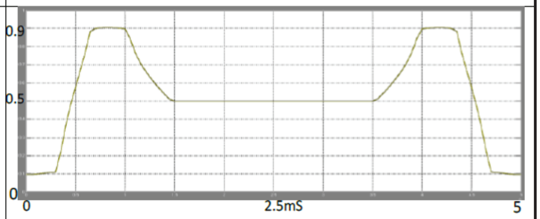
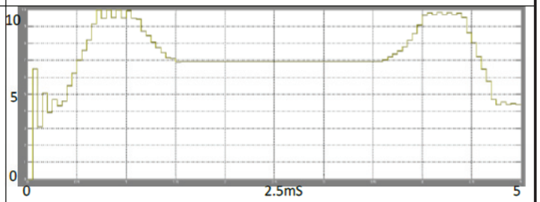
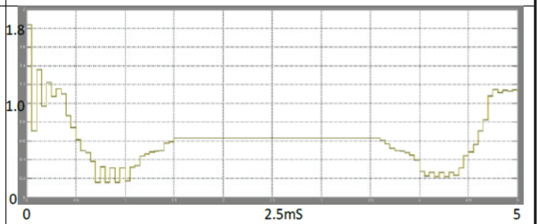
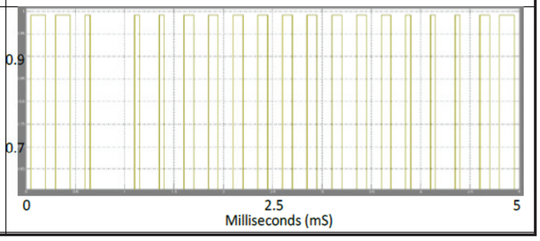
DESCRIPTION	Signal waveform
Outdoor light sinusoidal signal , frequency =100Hz, amplitude= 10	
Window shade Fuzzy Logic controller output signal	
Indoor light levels (feedback signal)	
LED's Fuzzy Logic controller output signal	
LED's current pulses	

Fig. 3.2: Signal Waveforms Incorporating the Effect of Outdoor Light

IV. Conclusion

The simulation model confirmed the objectives of the study. The simulation model demonstrated how a fuzzy logic controller can be used to process an outdoor light level signal in automatic control of a typical room's window shade position, and hence heuristically harvest daylight for energy efficient illumination of the room. The simulation model design also 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 level. The simulation model design tests also demonstrated that the lighting

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system LEDs could be dimmed off by a signal from either the room occupancy. However, the simulation results showed that the lowest level of the LEDs output 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.

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In 1994 he left the Universityand founded Elcom Systems Ltd. a company providing specialized hardware and software solutions for the telecommunication sector. As the CEO of Elcom Systems Ltd. he has developed and deployed several specialized telecommunication hardware and software solutions for many private and public sector companies and institutions.
In 2000, he rejoined the University of Nairobi and he is currently the Dean, School of Engineering. He is a Professional Engineer, a chartered Engineer in United Kingdom and a Member of IEEE.
He is the author of more than 30 articles and has created over 15 inventions under Elcom Systems Ltd. His research interests include broadband last mile connectivity devices, special materials and devices for solar power applications, internet of things devices, energy delivery automation and smart grids.