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Article

Automated dynamic lighting control system to reduce energy consumption in daylight

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SUMMARY
Buildings, which are responsible for the majority of electricity consumption in cities like Dubai, are often exclusively reliant on electrical lighting even in the presence of daylight to meet the illumination requirements of the building. This inefficient use of lighting creates potential to further optimize the energy efficiency of buildings by complementing natural light with electrical lighting. Prior research has mostly used ballasts (variable resistors) to regulate the brightness of bulbs. There has been limited research pertaining to the use of pulse width modulation (PWM) and the use of 'triodes for alternating current' (TRIACs). PWM and TRIACs rapidly stop and restart the flow of current to the bulb thus saving energy whilst maintaining a constant illumination level of a space. We conducted experiments to investigate the feasibility of using TRIACs and PWM in regulating the brightness of bulbs. We also established the relationship between power and brightness within the experimental setups. Our results indicate that lighting systems can be regulated through these alternate methods and that there is potential to save up to 16% of energy used without affecting the overall lighting of a given space. Since most energy used in buildings is still produced through fossil fuels, energy savings from lighting systems could contribute towards a lower carbon footprint. Our study provides an innovative solution to conserve light energy in buildings during daytime.

INTRODUCTION
There is an increasing focus on reducing electrical light energy consumption in buildings globally. Design-based solutions like wall windows, roof windows and technology-based solutions like automated lighting systems, have been used and recommended for new energy-efficient buildings (1, 2). Many new, energy efficient buildings have occupant sensing-based lighting systems in common areas like corridors and elevators. Commercial buildings have lighting schedules with full lights during peak hours and dim lights during off-peak hours. Although the energy consumed by the lighting systems of a building is considerably lower than the energy consumed by temperature regulation systems, there remains potential to further optimize the energy used by lighting systems in buildings (3).

Our study aimed to develop a novel automated solution to adjust light bulb brightness in the presence of sunlight to save energy. Prior studies have mainly focused on the effective use of light sensors and the architectural aspects of dimming light (3). In our experiments, we have used 'pulse width modulation' (PWM) for direct current (DC) lighting systems and phase control with 'triodes for alternating current' (TRIAC) for alternating current (AC) lighting systems. In the past, researchers have used rheostat-based ballasts, which are variable resistors that limit the current through an electrical load in combination with photosensors, to effectively use daylight (4). However, PWM and TRIAC-based techniques may be better than ballasts since ballasts reduce the power consumption by distributing it between the bulb and the resistor, instead of stopping the flow of current.

PWM in DC-driven lighting systems works by modifying the square wave form of DC voltage by alternating it between 5 V and 0 V. Each wave has a time period of 2 ms. This short time period means that the alternation is fast enough to provide an effective continuous voltage that is lower than the total supply voltage.

TRIAC-based phase control for AC-driven systems works by stopping the flow of current for a certain duration of time (the phase delay) after the sine wave changes from positive to negative or vice-versa. In the case of alternating current, PWM cannot be used since AC waves are sine waves, whilst DC waves are square waves.

We hypothesized that it would be possible to maintain the lighting within an environment while saving energy by regulating the space's artificial lighting to complement sunlight. We further hypothesized that there would be a linear relationship between the brightness of a bulb and the energy it consumes.

Our results indicate that both DC and AC light sources can be regulated. In the case of DC sources, there is a positive and quadratic co-relation between power consumption and brightness, and in the AC sources this co-relation is irregular and non-linear. Our experimental findings indicate that there is an opportunity to save energy in buildings by implementing a light sensor-based circuit. Using our experimental results, we have estimated the potential to save energy in the city of Dubai.

RESULTS
Our first goal was to establish whether both DC and AC light systems could be regulated. We also wanted to find the relationship between brightness and power consumption to calculate energy savings. We conducted two types of experiments: A Box Test to determine the feasibility of regulating DC lighting systems, and a Room Test to determine the feasibility of regulating AC lighting systems and to find the co-relation between brightness and power consumption.

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Our goal for the Box Test was to confirm that the brightness of a light emitting diode (LED) could be regulated using PWM. Our circuit for regulating LED brightness using a PWM system consisted of a BH1750 light sensor, red LED, and an Arduino microprocessor. The circuit was placed in a small box to simulate a room, and the light level within the box was changed using a phone flashlight. The Arduino was set to keep the lighting within the box, as measured by the BH1750 sensor, at 5 ± 0.50 lx **(Figure 1).**

In Box Test 1, no artificial lighting was introduced into the box, simulating complete darkness. The LED achieved a brightness of 5.00 lx within a period of 270 ms. The pulse width of the voltage supplied to the LED stabilized at 1.60 ms. In Box Test 2, the artificial light introduced in the box already met the 5.00 lx requirement. The LED did not switch on since there was no need for additional lighting. In Box Test 3, artificial lighting created a brightness of 2.50 lx to simulate partial lighting within the box. In this case, the brightness reached 5.00 lx, with the LED working at a pulse width of 0.59 ms. This adaptation occurred within 90 ms **(Figure 2).**

The DC experiments were conducted in a small box because the DC LED had a very low brightness output, especially in comparison to the room lights. The circuit was placed in a box to allow the sensor to accurately measure the impact of dimming. Furthermore, brighter DC lamps are difficult to source, need high power supply, and are not directly compatible with the Arduino. To find the relationship between the brightness of the bulb and the pulse width, an R^2 value was calculated for a linear fit of the data collected. The R^2 values for Box Tests 1 and 3 were 0.97 and 0.84, respectively, indicating a strong linear co-relation.

Energy savings for DC lighting systems was calculated using Ohm's law, which states that power is equal to the ratio of the squared voltage to the resistance. If lighting systems operated at 75% brightness, the savings in energy for DC based LED systems would be 44%, as calculated using Ohm's law. We assumed that the lights will be dimmed only for 25% of the time in which they are active, so the calculated power savings of 44% must be multiplied by 0.25 to determine the total power consumption savings. Therefore, for DC lighting systems, the energy savings will be 11% of total power consumption. After establishing the feasibility of regulating a DC lighting system, we conducted three tests in the room for AC lighting systems to simulate complete darkness, full brightness, and partial brightness **(Figure 3)**.

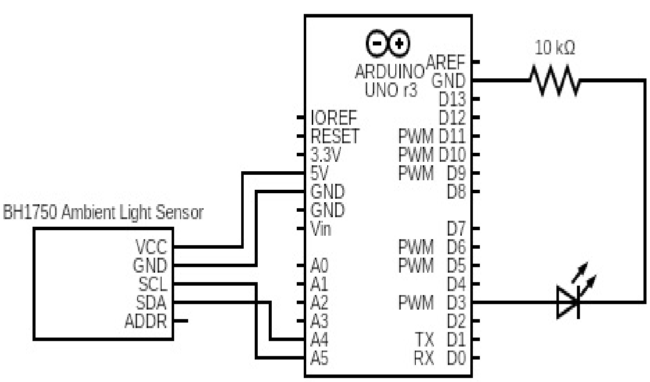

Figure 1: Circuit diagram for Box Tests 1, 2, and 3 to regulate LED with PWM for DC lighting systems. Brightness of the light was measured using a BH1750 sensor, while the pulse width of the LED was adjusted using the Arduino. The current passing through the LED was regulated by the resistor and also to prevent the LED from burning. Acronyms from the diagram are specified in Appendix 1.

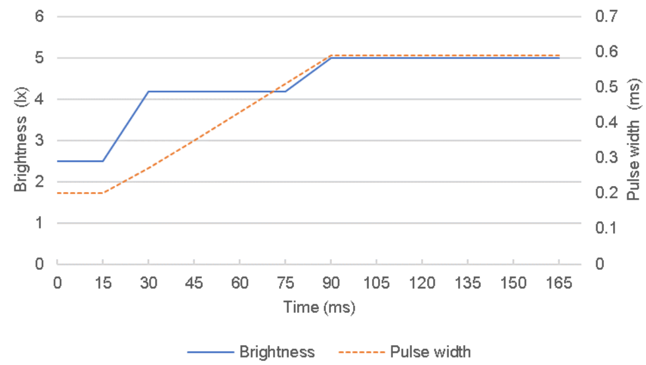

Figure 2: Response of the light sensor and the regulator circuit in Box Test 3 for DC lighting systems. An initial brightness of 2.50 lx was created using artificial light to simulate partial lighting in the box. Readings of both brightness and pulse width were recorded by the Arduino at 15 ms intervals.

In Room Test 1, the room lights were switched off to simulate complete darkness (0.00 lx). Next, the transformer was switched on. We observed that the bulb reached the minimum phase delay of 0 µs. The bulb brightness increased in steps and reached its maximum brightness 120 ms after the phase delay reached its minimum. The delayed change in brightness in this case was probably because of the sensor taking additional time to process and send results to the Arduino. The bulb stabilized at maximum brightness by the end of the test. The least count of the BH1750 sensor used was 0.83 lx, while the brightness readings of this test were observed at 0.20 lx intervals, creating a step-like graph. Sensors with lower least counts cannot integrate with the Arduino. Hence, the BH1750 was used. These results indicated that the system is suitable for a dark environment **(Figure 4).**

In Room Test 2, the room's lights were switched on simulating full brightness. We observed that the phase delay continuously increased up to 7500 µs. Initially, as the phase delay increased, drops in brightness were recorded. The brightness started increasing at a phase delay of 3000 µs and continued to increase until a phase delay of 7500 µs. Consistent drops in brightness were recorded after the phase delay reached 7500 µs before stabilizing at 37.50 lx**.** The least count of the BH1750 sensor used was 0.83 lx, while the brightness readings of this test were observed at 0.50 lx intervals, creating a step-like graph **(Figure 5).**

In Room Test 3, the target brightness was set to 33.00 lx, simulating partial brightness. The ambient room lighting at the start of the experiment was 30.00 lx. We observed that the phase delay decreased to 0 µs and stabilized for a short period of time at that value. However, a sudden increase in brightness, which can be attributed to the unstable room lighting, caused the phase delay to climb up to 7500 µs. Once again, the phase delay stabilized at 7500 µs. This cycle repeated again, with the phase delay going back down and then up. It then began to decrease, but stabilized at 4500 µs, with a brightness of 32.50 lx**.** In theory, the phase delay

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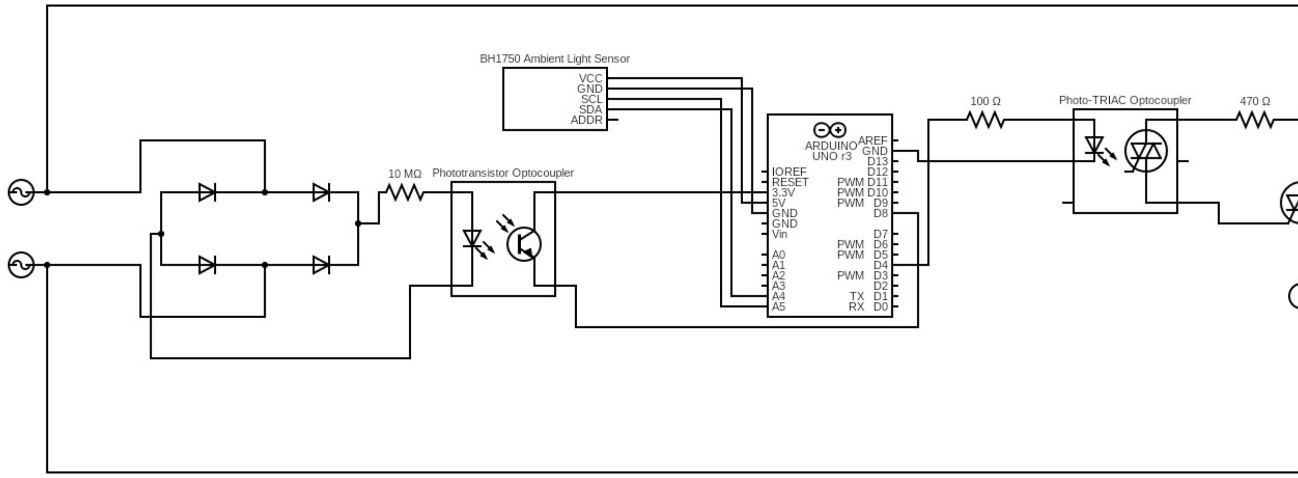

Figure 3: Circuit diagram for Room Tests 1, 2, and 3 for regulating AC lighting systems using a TRIAC to shift the phase of AC sine wave. Brightness was recorded using a BH1750 light sensor. A step-down 6-0-6 Centre-tap transformer connected to the 220 V Mains supply produced an AC output of 12 V. The zero-cross point of the sine wave was detected using four diodes that made a bridge rectifier. The Arduino provided the gate pulse of the TRIAC, based on the zero-cross point. Optocouplers were used to isolate the Arduino from the high voltage AC source. The bulb was regulated using TRIAC.

should have stabilized the first time it fell. However, due to a combination of the previously discussed communication time between the Arduino and the sensor, as well as the instability of the ambient lighting, the brightness barely exceeded the limits set in the program, thus causing the alternation of the phase delay. The system eventually stabilizing is a promising result, since in a sunlit room, such inconsistencies are less likely to arise **(Figure 6)**.

In Room Test 4, the goal was to determine the relationship between the brightness of the light bulb and the power consumed by it in an AC lighting system. The phase delay of the TRIAC was increased in 1000 µs intervals from 0 µs to 8000 µs. In this test, the voltage drop across the bulb at a particular phase delay was measured and the brightness at that delay was recorded by the sensor. The brightness of the bulb was measured using the light sensor in a completely dark room. We recorded three sets of the bulb's voltage and brightness readings at each phase delay, and used these values to calculate the bulb's power consumption **(Figure 7).** The power consumption of the bulb decreased with the decrease in brightness. There was a non-linear decrease in power in relation to brightness up to 50% of the total brightness. After that, the power consumption increased in relation to the minimum.

The bulb turned off completely past the phase delay of 7000 µs, while the voltage was 6 V past the phase delay of 6000 µs. This could be because the TRIAC's phase delay and the processing time of the Arduino caused the TRIAC to fire during the next half of the wave, causing an additional half-wave of voltage to be recorded. This may not happen in a 220/110 V Mains system since the time of the gate pulse of the TRIAC needs to be 10 µs only. This is because the Mains supply is higher current, and thus the holding current of the TRIAC can be met with a shorter pulse. In our tests, a gate

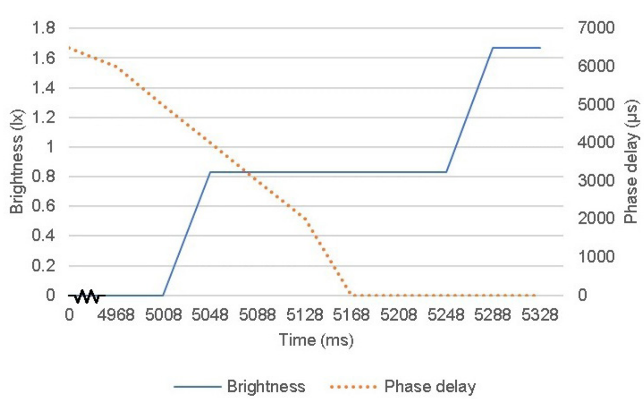

Figure 4: Graph indicating the circuit and light sensor response for Room Test 1 for AC lighting system in complete darkness. Complete darkness (0.00 lx) was created by switching off the room lights. Next, the transformer was switched on and the light was observed to switch on and reach its maximum brightness. The least count of the BH1750 sensor used was 0.83 lx, while the brightness readings of this test were observed at 0.20 lx intervals, creating a step-like graph.

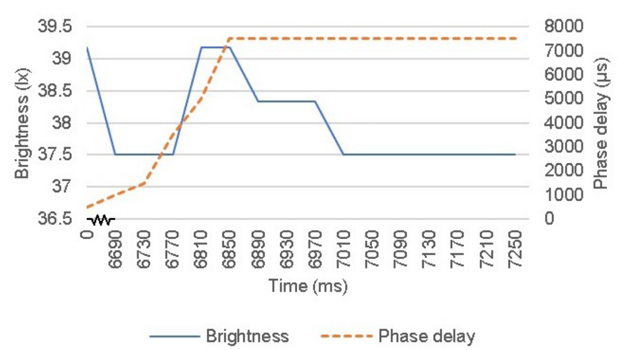

Figure 5: Graph indicating the circuit and light sensor response for Room Test 2 for AC lighting system in a room of full brightness. The room's lights and the experimental bulb were switched on at the start of the test with brightness at 38.30 lx and a starting phase delay of 500 µs. The room brightness stabilized at 37.50 lx at a phase delay of 7500 µs when the experimental bulb switched off. The least count of the BH1750 sensor used was 0.83 lx, while the brightness readings of Room Test 2 were observed at 0.50 lx intervals, thus creating a step-like graph.

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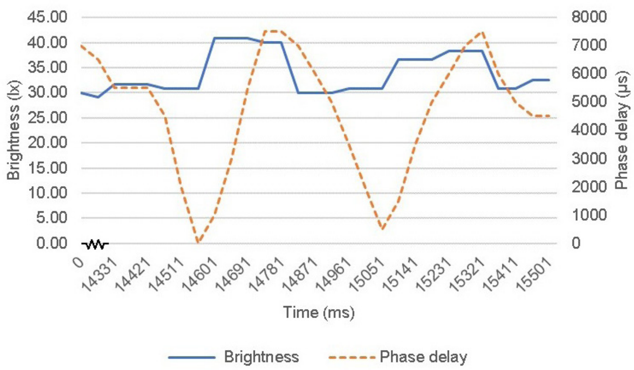

Figure 6: Graph indicating circuit and light sensor response for AC lighting systems when the target brightness was set to 33.00 lx in Room Test 3. An ambient room lighting of 30.00 lx was set at start of the test. This test simulated partial sunlight. The room brightness stabilized at 32.50 lx after 15 s. Inconsistent room lighting and communication time between the Arduino and the sensor caused the peaks and drops in phase delay.

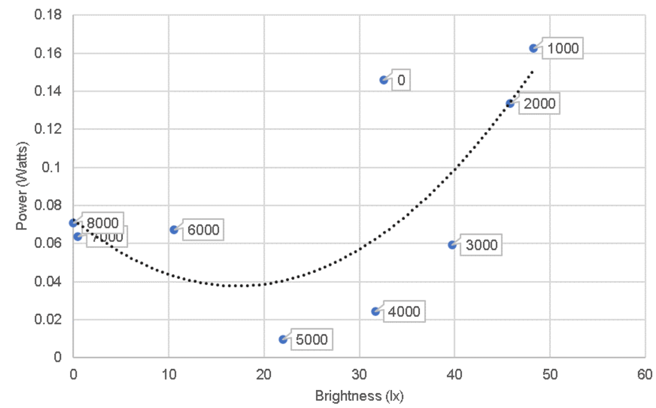

Figure 7: Graph indicating the relationship between the brightness of the light bulb and power consumption in Room Test 4 for AC lighting systems. Phase delay is represented by data point callouts. BH1750 sensor measured the brightness of the bulb in a completely dark room. Three sets of readings of the bulb's voltage were taken and its brightness at a particular phase delay. The dotted line represents a quadratic line of fit with $R^2 = 0.52$.

pulse of 2000 µs had to be used due to the lower current supply.

We established the relationship between the brightness of the bulb and the power it consumed using data from Room Test 4. We found that a quadratic fit best suited the data from this test. The R^2 value in the quadratic fit was 0.52. Although the quadratic fit is not particularly weak, it is also not very strong. For AC lighting systems, since the co-relation between brightness and power is relatively weak, the closest datapoint to 75% brightness was used. This point has a brightness of 39.72 lx (82% of total brightness). By taking the ratio of power consumption to brightness from our data, we calculated that power consumption at 82% brightness is 36% of the total energy consumption. Thus, power savings would be 64% of total power consumption. Since we assumed that the bulb would be dimmed only 25% of the time in which it is used, this value must be multiplied by 0.25, yielding energy savings of 16% of the total power consumption in AC lighting systems.

DISCUSSION

The goal of our Box Tests was to validate that PWM could be used to regulate a DC lighting system. Our results confirmed that DC bulbs can be regulated using PWM. We observed that the LED reached the target brightness in all three Box Tests, with the duty cycle, which is the percentage of the wave's time period for which 5 V is being supplied, being less than 100%. The effective continuous voltage provided is equal to the duty cycle multiplied by the total voltage.

In our experiments the total possible pulse width was 2 ms, and the voltage of the source was 5 V. Thus, if the bulb were to operate at 50% brightness, its voltage would be 50% of the total voltage. Based on Ohm's law, it can be concluded that a DC lighting system operating at 50% of its brightness would use 75% less energy than it would at full brightness. This finding is especially useful, considering that countries are shifting towards the use of LED lighting systems to meet carbon emission goals. Furthermore, LEDs are becoming more efficacious each year, and are more sustainable (5).

The goal of our Room Tests was to validate that a TRIAC based circuit can regulate the brightness of an AC bulb. Our results confirmed that the AC lighting system could also be regulated to complement its environment. However, AC systems took more time than the DC systems to regulate and stabilize: the AC system took 15 s to stabilize, whereas the DC lighting system took less than 1 s. This difference can be explained by the fact that the Arduino took longer to initialize, since the program was longer compared to that of the DC system.

In Room Test 4, we established the relationship between the brightness of the bulb and the power it consumed. The R^2 value of a quadratic fit between the brightness of the bulb and power consumption was 0.52. This does not necessarily imply a lack of co-relation between power and brightness, but suggests that a higher-order non-linear relationship may be more appropriate (**Figure 7**).

Using our test data, we calculated energy savings for DC and AC lighting systems. Buildings in Dubai consume 53.18 billion kWh of energy in a year. On average, lighting systems are responsible for 7% of the total energy consumed by a building (6,7). Thus, lighting systems in Dubai consume 3.72 billion kWh energy in a year.

For DC lighting systems, savings would be 11% of the total lighting power consumption, which is ~407 million kWh per year. The energy savings for AC lighting systems would be 16% of total light energy consumption which is ~590 million kWh per annum and equates to about one percent of the total energy consumption of Dubai. In order to achieve these savings, every building would have to deploy appropriate TRIAC based circuits. TRIAC based circuitry would not require any new infrastructure and may be accommodated within existing buildings' electrical circuits.

Some limitations of our study are that the experiments were conducted at 12 V AC and 5 V DC, but an actual system would run at 120/220 V AC or 12/24 V DC. Our next steps would include trials with Mains systems in buildings and attempts to implement the idea. A possible challenge to implementation could be converting the complex circuit into a compact system.

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MATERIALS AND METHODS

Box Tests to confirm the feasibility of regulating a DC lighting system

An Arduino Uno microcontroller developed by Arduino.cc and an AdaFruit BH1750 ambient light sensor were used for our experiments. List of Arduino port acronyms used in circuit diagrams is provided in **Appendix 1**. The Arduino's 5 V and Ground ports were connected to the Voltage Common Collector (VCC) and Ground ports of the BH1750 light sensor. The serial clock pin (SCL) and serial data pin (SDA) ports of the sensor were connected to the analog ports A5 and A4 of the Arduino respectively. As per the data sheet of the AdaFruit BH1750, the sensor has an error margin of ±1.00 lx. A 2.4 V red LED was connected to the digital port D3 of the Arduino and to ground (**Figure 1**).

The circuit was placed in a small box of dimensions 11 cm x 7 cm x 7 cm to simulate a room. The light level within the box was changed using a phone flashlight to simulate complete darkness, full brightness, and partial brightness in Box Tests 1, 2, and 3. The Arduino was set to keep the lighting within the box, as measured by the BH1750 sensor, at 5 ± 0.50 lx.

The readings of pulse width and time were recorded through the Arduino Integrated Development Environment (IDE). The time intervals were each iteration of the Arduino's loop function. The pulse width, which was determined through the program, was printed to the console for readings. The brightness of the setup was recorded using the BH1750 sensor, where the lux value was also printed to the console of the Arduino IDE. The program used for this experiment is included in **Appendix 2**. An R^2 co-relation coefficient was calculated for linear fits of the brightness when graphed against pulse width for Box Tests 1 and 3 to ascertain the relationship between brightness and voltage. Readings of Box Test 2 (full brightness) were omitted, since the bulb switched off, and brightness remained constant, leaving

$$P = \frac{V^2}{R}$$

only one datapoint that was repeated multiple times. Power consumption was calculated using Ohm's law.

Room Tests to confirm the feasibility of regulating an AC lighting system

For the Room Tests, the Arduino's 5 V and Ground ports were connected to the VCC and Ground ports of the BH1750 light sensor. The SCL and SDA ports of the sensor were connected to the analog ports A5 and A4 of the Arduino respectively. A 6-0-6, 500 mA centre-tap step-down transformer was connected to the Mains supply to provide the AC supply for the system. The transformer output was passed through a full wave bridge rectifier made using four 1N4001 diodes. The positive output from the rectifier was connected to the anode of the SHARP PC817 phototransistor optocoupler through a 10 MΩ resistor. The cathode was connected to the negative output. The collector of the PC817 was connected to the Arduino's 3.3 V supply and the emitter was connected to Digital port D8. This part of the circuit formed a zero-cross detection system, which is necessary to drive the TRIAC.

Digital port D4 was set to output and connected to the anode of the MOC3020 photo-TRIAC optocoupler through a 100 Ω resistor. The cathode of the optocoupler was connected to ground. One of the transformer outputs was connected to main terminal 2 of the BT139 TRIAC. This output was passed through a 470 Ω resistor into one of the main terminals of the MOC3020. The other main terminal of the MOC3020 was connected to the gate pin of the BT139 TRIAC. Main terminal 1 of the BT139 was connected to a GutReise E10 bulb, rated at 12 V, 0.25 W. The other terminal of the bulb was connected directly to the second output of the transformer (**Figure 3**).

Brightness readings were taken using the BH1750 Ambient Light sensor and the readings from the sensor were printed to the console of the Arduino. The phase delay of the TRIAC was determined using programming and was also printed to console. The times of the readings were taken from the timestamps provided by the Arduino when displaying console messages.

For the Room Tests, the circuit was placed in a closed room, with the ambient lights switched on or off as indicated. For Room Test 1, the ambient lights were switched off and the room was in complete darkness. The target brightness was set to be higher than the lighting system's maximum. For Room Test 2, the ambient lights were switched on, and the brightness target (final set-point) was set to be lower than the lighting system's minimum. For Room Test 3, the ambient lights were switched on, but the target brightness was set to 3.00 lx higher than the zero-reading of the brightness with the ambient lights on. In this case, the target brightness (final set-point) was 33.00 lx. The program used for this experiment is included in **Appendix 2**.

Room Test for correlating brightness and power consumption in an AC setup

For Room Test 4, a multimeter was connected as a voltmeter across the terminals of the bulb. The least count of the multimeter was 0.01 V. The room lights were switched off, and the readings were taken in complete darkness.

The phase delay was programmed to change from 0 μs to 8000 μs in 1000 μs intervals. The voltage drop across the bulb was measured each time. The brightness of the bulb was measured using the BH1750 light sensor, and the readings were printed to the Arduino IDE console. Each reading was taken thrice and averaged to eliminate any random variation. The program used for this experiment is included in **Appendix 2.**

$$P = \frac{V^2}{R}$$

The power consumption of the bulb was determined by the formula:

The resistance of the bulb was determined by its rating,12 V, 0.25 W. An R^2 value was calculated for the quadratic fit to approximate the power consumption at various brightness levels and establish the co-relation between power and brightness.

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APPENDIX 1 – List of Acronyms Used in the Arduino circuits

IOREF – input/output reference

RESET – Reset

3.3V, 5V – Output pins for 3.3 and 5 V respectively

GND – Pins connected to ground

Vin – Voltage input

A0 – A5 – Analog pins of the corresponding number for input

AREF - Analog reference

D0-D13 – Digital pins of the corresponding number capable of digital input and output

PWM – Denotes a digital pin capable of Pulse Width Modulation

TX – Digital data transmitter

RX – Digital data receiver

APPENDIX 2 – Programs used

GitHub repository: Tanay-Jagan/Dynamic-Lighting-Control-System: Code Files for the Arduino Based Dynamic Lighting Control System(github.com)