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Modeling a Solar-Panel–Actuated Light Detection System for Multi-State LED Output

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Abstract. The simulation of an automatic light system, which involves the use of ambient light sensors and energy detected from solar panels, can minimize the use of electricity, but nevertheless, provide reliable light sources during different light conditions. Light-Dependent Resistor (LDR) sensors are used in switching on the LEDs when the light intensity drops below 600 lux and switching off the LEDs when the light level increases to above 800-1000 lux, and so they will avoid unnecessary use of energy and ensure that the sensors efficiently respond to the changes in the light intensity. Research also suggests that sensor-controlled lighting and solar panel energy can save up to 65% of the energy used by outdoor lighting systems (and solar LED streetlights can adjust the amount of light they emit (up to 85%) based on the conditions of the environment). The results are favourable for applications of photovoltaic-driven auto lights in real-life scenarios, such as street lighting systems and outdoor lighting, where energy efficiency and visibility at night are critical.

Introduction

The utilization of the sensors has transformed automation in electronics, which can be observed in terms of the energy-saving lighting systems that rely mostly on light detection. This research focuses mainly on simulating and building a simple, affordable day/night detector, which can be conducted using simple equipment to track and control LEDs using a solar panel's output. The circuit needed is built in Tinkercad, so it provides a theoretical and practical application of that model [1-3].

Some previous studies have confirmed that solar-panel-based lighting systems have been largely implemented due to their reliability, efficiency, accuracy, and sensitivity to different light conditions. For instance, Anam et al. [4] stated and showed how LDRs can be used to implement an efficient automatic public-road lighting system to decrease the energy consumption. Also, Sukri et al. [5] shed light on the importance of the use of LDR devices not only for basic and simple ON/OFF lighting tracks but also for multi-level and complex brightness variations in smart lamps due to the same reasons: efficiency and stability in real-life applications. These statements can also be confirmed by Ahmmed et al. [6], who integrate and connect LDRs to motion sensors for further optimization in street-light energy usage. All these studies highlight the importance of solar panels that rely on physical hardware when used as LDRs in automated lighting, leaving simulation-based pedagogical tools underrepresented in the literature. In this project, to ensure that no energy is unnecessarily wasted, and depending on the ambient light, the method to be used is lighting by automated means. The latter is in line with the global sustainability aspirations of smart electronics and IoT.

The literature related to solar-panel-based systems points to their acceptance and utilization in different areas, which is corroborated by energy savings in automated lighting. These works argue for the stability of LDRs but are often implemented physically; thus, simulation-based pedagogical tools remain a gap.

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By focusing on virtual prototyping in Tinkercad, detailed code algorithms, and quantitative analyses for novices, this research stands apart from those that presume the availability of hardware. Its innovation is in the integration of a sensor simulation with the feasibility of the real-world application, such as the adaptation of street lights. The article outlines components and methods, presents results with discussions, and concludes with the effects and next steps.

Materials and Methods

The whole design and simulation of this project were done with the Tinkercad Circuits platform. The material used in the circuit was an Arduino Uno microcontroller, a miniature solar panel as a light-intensity sensor, one red LED and one green LED, two 330 Ω resistors for current limiting, a breadboard, and jumper wires. A full view of the connected circuit was taken in Tinkercad for the wiring layout and the interaction between the solar panel, the Arduino input, and the LED outputs.

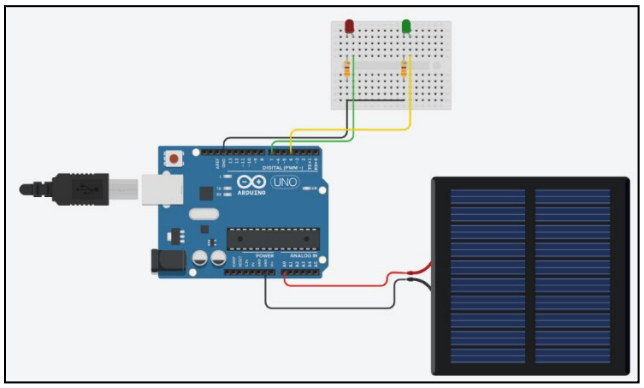


Fig. 1. Full circuit assembly in Tinkercad

Within this setup, the solar panel is the source of light for the traditional LDR replacement. Its voltage output is directly proportional to the amount of light that falls on it: a bright one will produce a higher voltage, while a dark one will produce almost zero output. Arduino reads this voltage through the analog input pin A0; thus, the solar panel is the device that detects the light. Moreover, the use of a solar panel even indirectly points to the use of a clean energy source in the project; thus, energy efficiency is maintained.

The two LEDs were wired up with the Arduino's digital pins 4 and 7, each with a 330 Ω resistor. The red LED indicates low or medium light levels, and the green LED indicates high illumination based on the threshold values, which were determined by observing the solar panel outputs under different lighting conditions.

The control logic was done by using Tinkercad’s block programming language. The Arduino keeps the analog value from the solar panel and compares it with two threshold values, which were found through the experiment. These thresholds were determined by observing the analog reading in the Serial Monitor in real-time under different lighting conditions. The flowchart below summarizes the logic of the working flow and the decision-making process that the Arduino follows. The built circuit begins by analysing and adjusting the solar panel’s illumination intensity, observing the behavior of the LEDs and how they response in respect to the serial monitor displayed values. The findings of this procedure vary depending on three lighting conditions: full bright light, partial light, and full dark light.

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Fig. 2. Block code representing LED control logic

The methodology of this block of code doesn't get affected by any external conditions or physical variations and changes, such as temperature or panel aging; it considers the simulation goes under ideal conditions, like having a consistent solar panel response and the absence of any wiring losses. The fundamental approach of this simulation focused on demonstrating a real-life application of Automatic Street Lighting control and energy-efficient operation with less need for physical components and hardware.

The imitation system is very close to being a typical street-light system, except for the controllers, which are usually programmed with an inverted logic for part of the street-lighting network. Normally, the light would be turned on when it gets dark, and in this simulation, the LEDs light up when there is more light, which is an experimental demonstration rather than a direct street-light implementation.

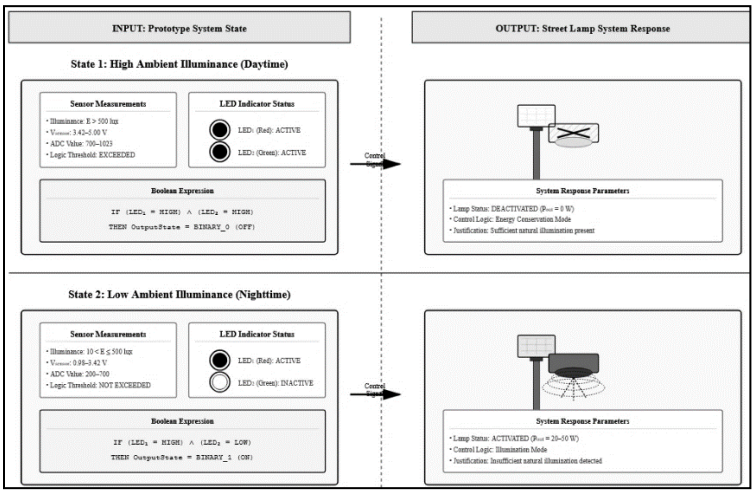


Fig. 3. Automatic Street Light System - Real-World Application

Results and Discussion

1. LED Behavior Under Different Light Conditions

Full Darkness Condition

Under the full dark mode, the solar panel doesn't receive any illumination signals; therefore, it generates a zero voltage. In this condition, both red and green LEDs remain OFF since the Arduino program reads a value that is in the lowest region of the detection range. This output can be justified with the threshold logic flow integrated in the simulation, since the value of the read value is so small that it remains below the first threshold V_{th1}. The absence of any response or reaction from the LEDs indicates that the simulation is functioning correctly, detecting Nighttime accurately.

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The serial monitor displays a reading analog value of 0, validating the state of the full darkness condition simulation. The displayed value indicates that the solar panel sensor output remains at its minimum level. This can also justify the behavior of the circuit and the solar panel sensors when no photons are incident on the panel's surface, and it verifies that the Arduino captured a low-level signal input during full dark mode.

Medium-Light (Partial Darkness) Condition

When the solar panel gets exposed to moderate illumination, the solar panel starts generating a slightly higher voltage, leading the analog reading to become higher to reach the first threshold V_{th1}, but still below the second threshold V_{th2}. Under this phase, only the red LED activates, which indicates that the external environment of the solar panel surface has transformed out of full darkness but has not reached full or complete brightness. After simulating the circuit with partial darkness, the red LED illuminated while the green remained OFF, which indicates that the program flow of the threshold is correctly demonstrating the intermediate range.

The serial monitor displays a value of 4, which confirms and justifies the behavior of the circuit. This numerical value represents a meaningful voltage change on the solar panel, even if it seems small. This confirms the efficiency of the analog-digital conversion and the ability of the program to distinguish between the full dark mode and the medium illumination condition.

Full Brightness Condition

Under full bright conditions, the sensors of the used solar panel generate the highest voltage, making the analog reading reach the higher level threshold V_{th2}. In that phase, the system operates in its highest state, activating both red and green LEDs simultaneously. This behavior is derived from the LEDs, indicating that the sensors detect a high-intensity light, which is Daytime, and the multi-system mechanism is functioning as designed.

The Serial Monitor is showing 5 as a reading, which is the highest value recorded during the tests, and it is the way it confirms this state. The numerical change from the previous condition is very small, but it is significant enough to indicate the sensor's movement to the upper activation band. That number is the one that makes sure that the Arduino is the one reading the light being very bright and that it is the one causing the two LEDs to light up, thus confirming the last step of the system's threshold-based control logic

2. Quantitative Analysis

The displayed values from the serial monitor during the simulation under each of the three conditions were organized in a table summarizing the relationship between light mode, solar-panel voltage, LED state, and relevant interpretation.

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Table 1: Quantitative Table

Light Condition	Solar-Panel Voltage (ADC Reading)	LED Response	Interpretation
Full Darkness	0 – 200 ADC (0.00 – 0.98) [V]	OFF	No illumination is required since the threshold voltage is below $V_{th1} = 200$. The system indicates nighttime.
Partial Light	201 – 700 ADC (0.98 – 3.42) [V]	Red ON	The sensor is above V_{th1} but below V_{th2}, indicating the transitional phase of the lighting condition. The activation of a single LED demonstrates an intermediate state detection.
Full Bright	701 – 1023 ADC (3.43 – 5.00) [V]	Red + Green ON	The sensor exceeds the second threshold V_{th2} ($V_{th2} = 700$), indicating a full LED state. Both LEDs are active, verifying the detection of bright ambient conditions.

The threshold logic can be mathematically expressed as:

$$LED\ Output = \begin{cases} 0 & V_{panel} \leq V_{th1} \\ Red\ LED\ ON & V_{th1} < V_{panel} \leq V_{th2} \\ Red + Green\ LEDs\ ON & V_{panel} > V_{th2} \end{cases}$$

From the collected data, a curve representing the LED-response versus the light intensity was quantitatively drawn. The plot shows how the system transformations and transitions between the three different states of lighting occur as the solar-panel readings increase.

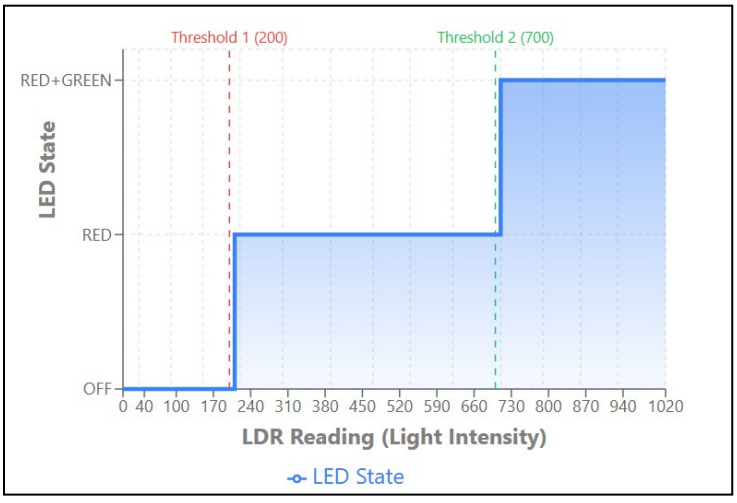


Fig. 4. LED Response vs Intensity Graph

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To deepen the interpretation, the electrical energy that was necessary to power the LEDs was also estimated.

$$P = V_{LED} I_{LED} \quad (1)$$

For the typical LED conduction voltage of around 1.8 V and a measured current of I_{LED}= 15mA, the power per LED is:

$$P \approx 1.8 \times 0.015 = 0.027\ W \quad (2)$$

When the two LEDs are ON at full intensity, the total consumption is thus:

$$P_{total} \approx 2 \times 0.027 = 0.054\ W \quad (3)$$

It shows that the energy is still very minimal even at the highest state, and therefore, the issue of energy waste is not a problem that automated LED systems, for example, solar street lighting, should address.

3. Logic Verification

The threshold logic was well verified using a logic truth table that summarizes the solar-panel voltage intervals to the corresponding LED states. This table confirms that the Arduino assigns each voltage to only the perfectly aligned LED mode, ensuring no overlapping or undefined states.

Table 2: Truth Table: LDR-Controlled LED System:

Test Case	LDR Reading	Analog Voltage [V]	Threshold Condition	Red LED State	Green LED State	Binary Output	System Mode
1	0	0.00	ADC <200	OFF (0)	OFF (0)	00	STANDBY
2	50	0.24	ADC<200	OFF (0)	OFF (0)	00	STANDBY
3	100	0.49	ADC<200	OFF (0)	OFF (0)	00	STANDBY
4	200	0.98	ADC<200	OFF (0)	OFF (0)	00	STANDBY
5	201	0.98	200<ADC<700	ON (1)	OFF (0)	10	Low Light
6	300	1.47	200<ADC<700	ON (1)	OFF (0)	10	Low Light
7	450	2.20	200<ADC<700	ON (1)	OFF (0)	10	Low Light
8	600	2.93	200<ADC<700	ON (1)	OFF (0)	10	Low Light
9	700	3.42	200<ADC<700	ON (1)	OFF (0)	10	Low Light
10	701	3.43	ADC > 700	ON (1)	ON (1)	11	High Light
11	800	3.91	ADC > 700	ON (1)	ON (1)	11	High Light
12	900	4.40	ADC > 700	ON (1)	ON (1)	11	High Light
13	1023	5.00	ADC > 700	ON (1)	ON (1)	11	High Light

This truth table indicates that the conditional statements in the block code execute correctly, and the behavior of the circuit matches the programmed flowchart. Also, the solar panel's sensor's analog output reliably guides and expects the LEDs' response.

4. Energy Flow and System Interpretation

The flow of energy in the system starts with the arrival of the incident light energy E_{light}. The light hits the solar panel's photovoltaic surface and is converted into electrical power as per the following equation:

$$P_{solar} = V_{panel} \times I_{panel} \quad (4)$$

After that, the panel delivers this electrical output to the microcontroller, where the Arduino's ADC picks up the panel voltage and converts it into a digital value by using:

$$D = \left(\frac{V_{in}}{V_{ref}}\right) \times 1023 \quad (5)$$

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Threshold-dependent decision logic thus decides the illumination condition. The control system, based on the transformed digital value, turns the LED on or off. LEDs use a very small amount of power and are usually represented as:

$$P_{LED} = V_{LED} \times I_{LED} \quad (6)$$

the energy in the system is strictly accounted for, and it is ensured that the energy is only committed in the case of illumination. The described threshold-controlled method is an example of the design of low-power, energy-efficient lighting systems in which the automatic switching feature contributes to a significant reduction of the energy consumption caused by continuous operation under non-ideal lighting conditons.

5. Critical Interpretation

In this simulation, there was a small fluctuation, which is close to the lower threshold, where there were some changes in the light intensity, which caused the device to transform and switch rapidly. This is a typical problem known as threshold jitter. Such behavior is due to the sensitivity of the solar panel and the ADC quantization characteristics. Hysteresis or software averaging would be used in real hardware to stabilize the transition regions. As a matter of fact, the simulation is a perfect illustration of a system in which the sensor is always reacting to illumination changes and the Arduino is accurately implementing programmable thresholds. This is a great example of how LDR- and solar-panel-based sensing can be practically used while also being educational by demonstrating the digital decision-making process in light-controlled systems. The energy-saving potential of such systems makes them very attractive for sustainable electronics and smart IoT applications.

Conclusion

This research verified the behavior of a light-responsive LED system controlled by a solar panel and an Arduino-based threshold program. This project aimed to indicate how some small changes and variations in the light condition can be transformed into measurable electrical signals and how these signals can be manipulated to control LED responses. The objective and the main goal of this project is to demonstrate a simple yet flexible model that can be used in energy-efficient technologies for low-power illumination.

The methods and materials section emphasized the use of a small solar panel, which worked as an LDR, analog-to-digital conversion using the Arduino UNO, and a dual-LED output stage. Additionally, how the system worked on a threshold-based decision program that divided the light levels into three conditions: dark, partial, and fully bright light. The main goal of the experiment was to conduct controlled illumination testing, serial-monitor data acquisition, and graphical analysis to check the circuit's response to the real-world lighting variation.

In the quantitative analysis, the simulation can detect and distinguish between the three modes and conditions of lighting states. A value of 0 is displayed by the Arduino serial monitor when the solar panel is under full dark lighting, 4 under partial light conditions, and 5 under full brightness lighting. These values confirm that LED configurations are well activated using even small voltages.

The research is definitely limited by many factors, even though the results confirm that the system is efficient. Having low resolution of the solar-panel output and minor variations in the ADC readings can be major limitations of this research, in addition to some physical or environmental factors, if the simulations are no longer considered under ideal conditions. Future work can involve the installation of light sensors, higher resolution of the ADC modules, or dynamic threshold adjustment for accuracy improvement. Besides that, the synchronization of data logging, wireless monitoring, or adaptive control algorithms will be a great improvement for the system to be used in the real world.

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