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A Compact and Affordable System for Verifying Malus's Law in Classroom Settings

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Abstract

This paper presents a cost-effective and automated system for verifying Malus's Law using an Arduino microcontroller and a Light Dependent Resistor (LDR). Traditional setups often rely on photodiodes and manual data recording, making them less suitable for modern educational environments. In contrast, the proposed system integrates Arduino with Python-based real-time graphing, reducing observational errors and streamlining the experiment. The setup not only enhances accuracy but also promotes hands-on learning, making it ideal for ICT (Information and Communication Technology)-enabled classrooms. Experimental results closely align with the theoretical cosine-squared ($\cos^2\theta$) model, validating the system's reliability. This approach offers a practical, scalable, and affordable solution for physics laboratories and STEM (Science, Technology, Engineering, and Mathematics) education.

Keywords: Malus's Law; Arduino; Light Sensor; Python Graphing; Polarization Study; Real time Feedback; STEM Lab Kits

Introduction

Malus's Law is fundamental in understanding the behavior of polarized light as it passes through optical components such as polarizers and analyzers. It finds applications in various fields, including photography, quantum optics, liquid crystal display (LCD) technology, and stress analysis in transparent materials. However, traditional experimental setups for demonstrating Malus's Law are often costly, complex, or rely heavily on manual measurements—making them less accessible in modern educational environments.

To address these limitations, this study proposes a low-cost and automated solution using Arduino, an open-source microcontroller platform. By integrating an Arduino with a Light Dependent Resistor (LDR), the setup enables interactive and hands-on learning, allowing students to directly connect theoretical concepts with real-time experimental data. This paper presents the development and evaluation of this compact system, emphasizing its practicality, affordability, and potential impact in STEM and ICT-enabled physics education.

Literature Review

Numerous studies have explored experimental methods to demonstrate Malus's Law using traditional optical tools. Ghosh and Banerjee [1], for instance, utilized a photodiode-based setup to measure light intensity, while Khan et al.[2] developed a microcontroller-driven polarization analyzer for improved automation. Despite these advancements, there has been limited focus on using low-cost sensors such as Light Dependent Resistors (LDRs) in educational contexts.

Most existing setups either lack real-time data visualization or depend on costly hardware, making them less feasible for widespread classroom implementation. The integration of open-source platforms like Arduino and Python offers a promising solution to these challenges [3]. These tools enable real-time plotting, ease of customization, and scalability—making the experiments more interactive and accessible [4]. Furthermore, such approaches promote interdisciplinary learning by bridging concepts from electronics, programming, and physics [5].

Methodology

Two experimental setups were developed for comparison. The traditional setup used a tungsten filament bulb for illumination and a polarizer–analyzer pair to control light polarization. A photodiode was used as the light sensor, and intensity readings were manually recorded using a multimeter. Data collection and graph plotting were done manually, which introduced the possibility of human error.

The proposed automated setup employs a Light Dependent Resistor (LDR) as the light sensor, connected to an Arduino Uno that reads analog values through an analog-to-digital converter (ADC). The analyzer's angle can be adjusted manually or controlled via a servo motor for improved precision. Real-time data is transmitted to a Python script using serial communication, where Matplotlib is used to plot the light intensity against the analyzer angle.

A calibration process using a lux meter was carried out to map raw ADC values to approximate light intensity levels, improving measurement accuracy. The use of a voltage divider circuit allows the Arduino to interpret changes in resistance due to varying light intensity, and the plotted data visually represents the $\cos^2\theta$ behavior predicted by Malus's Law.

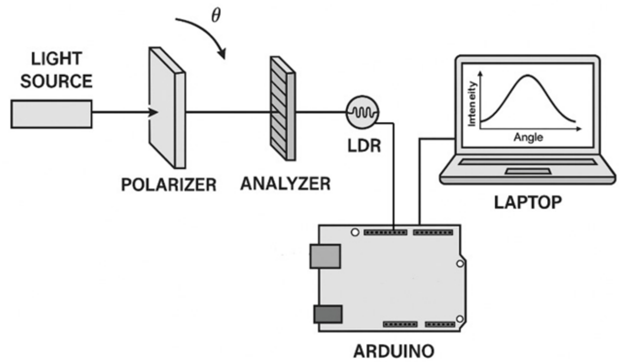

Fig 1. Experimental setup for verifying Malus's Law using Arduino, LDR, and real-time Python plotting

The LDR is connected to a voltage divider, and its output is read via the Arduino's analog pin. These values are transmitted via serial communication to a Python script, which plots light intensity against analyzer angle. Calibration is performed using a lux meter to map raw ADC values to actual light intensity.

Results and Observations

The results confirm a strong correlation between the observed and theoretical values of light intensity, in accordance with Malus's Law ($I = I_0 \cos^2\theta$). The Python-generated graph displays a smooth cosine-squared curve, validating the experimental setup.

To assess the system's accuracy, the measured data was compared with theoretical predictions using the Mean Squared Error (MSE) method. The theoretical intensity profile $I(\theta)=I_0 \cos^2\theta$ was generated at 1° intervals using I_0 measured at $\theta = 0°$. The mean-squared error (MSE) between the experimental and theoretical curves, averaged over three independent trials, was 5.6 % (range 5–7 %). Given the ±4 % linearity error of the LDR and the ±2 % fluctuation in ambient light, the average MSE was found to be in the range of 5–7%. This indicates a reasonably high level of precision, especially considering the use of a low-cost LDR sensor. The margin of error was primarily attributed to factors such as sensor non-linearity and ambient light interference, which were mitigated through shielding and calibration.

[1] Ghosh and Banerjee introduced the use of Arduino in educational labs to demonstrate light polarization phenomena in a simple and interactive manner.

[2] Khan et al. created a microcontroller-driven analyzer specifically designed for polarization experiments, demonstrating improved automation and experimental control.

[3] A similar Arduino-based setup was developed by Ghosh and Chakrabarti to log optical intensity in real-time, improving measurement precision during polarization studies.

[4] Sharma and Rathi proposed an affordable toolkit using Arduino for various undergraduate optical physics experiments, focusing on accessibility and cost reduction.

[5] Zope and Chavan designed a budget-friendly Arduino-based polarimeter, offering an effective low-cost solution for hands-on learning in physics labs.

Table 1. Comparison Table

Feature	Traditional Setup (Photodiode & Multimeter)	New Setup (LDR & Arduino)
Light Source	Yellow tungsten bulb (broad spectrum)	Any light source (Flexible)
Sensor Used	Photodiode (generates current)	LDR (resistance-based intensity detection)
Intensity Measurement	Measured via current using a multimeter	Directly processed by Arduino
Data Collection	Manual recording of readings	Automated & real-time plotting
Graphing	Requires manual plotting	Auto-generated via Python
Automation	Fully manual (angle & data recording)	Can be automated (motorized polarizer + live graphing)
Cost	More expensive (photodiode, precise multimeter)	More affordable (LDR + Arduino)
Ease of Use	Requires careful calibration	Simple plug-and-play setup
Error Reduction	Prone to human error (manual reading & recording)	Minimizes human error via automation

Educational Impact

This project introduces students to a multidisciplinary learning experience where physics, electronics, and programming intersect. Key educational benefits include:

- Improved Visualization: Real-time graphing enhances conceptual understanding.
- Skill Development: Encourages familiarity with Arduino programming, Python scripting, and data visualization tools.
- Active Learning: Promotes experimentation, inquiry-based learning, and analytical thinking.
- Accessibility: Makes complex experiments affordable and approachable.
- Student Engagement: Hands-on, interactive setups tend to increase participation and interest in physics.

Such integrations are ideal for STEM curricula and help bridge theoretical knowledge with practical application.

Discussion

The automated model for verifying Malus's Law demonstrated significant advantages over conventional methods. The system reduces manual errors, speeds up data analysis, and enhances the user experience through live visual feedback. However, challenges such as ambient light sensitivity and LDR non-linearity required mitigation. These were effectively addressed using shielding materials and calibration routines.Future improvements could include full motorization of the analyzer, Bluetooth or Wi-Fi-based data transmission, integration with mobile apps, and on-device displays (e.g., LCD or OLED modules). These enhancements would further increase the system's appeal and adaptability for remote learning or classroom demonstrations.

Conclusion

This study successfully demonstrates a compact, low-cost, and automated system for verifying Malus's Law using Arduino and Python. The setup offers high educational value by simplifying the experiment and integrating real-time feedback, making it especially suitable for ICT-based and STEM-focused learning environments. With potential for further expansion and customization, this system paves the way for more accessible and engaging physics laboratory experiences.

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