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ORIGINAL ARTICLE

Phototactic Motion with Arduino: A Teaching Instrument Prototype to Demonstrate Interdisciplinary Concepts in STEM-related Courses

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ABSTRACT - The phototactic device described in this paper was inspired by a solar tracker. The industrial solar tracker itself is a well-established structure. The increased accessibility of microcontrollers, open-source code, and 3D printers to education providers and students at the tertiary level has fueled the development of numerous constructs based on its design and function. Tapping into this trend, the phototactic device is thought to be a potential pedagogical tool for STEM courses offered at the secondary school level and foundational level. The design of the device comprises a dual-axis solar panel and a sundial. The sensors from the sundial generate inputs for the programme in the Arduino to compute the optimal tilt angles for the servos. Ultimately, the programme optimises the position of the mounted solar panel for maximum sunlight exposure. The objective of this paper is to introduce an educational version of solar tracker based on Arduino UNO. The students can learn programming, circuitry as well as conducting data analysis in a practical laboratory setup. In this paper, we are reporting on the various perspectives through which lessons can be planned to use this prototype as a pedagogical tool.

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INTRODUCTION

With the rise of programming languages of varying levels of complexity and the widening use of microcontrollers, emulating industrial-scale machinery on a modular scale to facilitate teaching and learning has started to become a trend in academia. The trend is noticeably catching on from two perspectives. The first is work produced as a result of project-based learning. They report on the technical specifications of the developed prototype to meet research and development (R&D) in the industry or in academia. By manipulating the designs, the programming language used, and their mechanism strategies, the performance of the project was measured to reflect on the designer's performance [1],[2],[3]. From the second perspective, the study on the impact of the educational implementation of the industrial-inspired prototypes was conducted [4],[5],[6]. The trends sprung from the current challenges in the education system. Globally, coding literacy has gained recognition and has been identified as an employable skill [7]. Despite Malaysia's current Industrial Revolution 4.0, the education arena is plagued by students' lack of interest in pursuing STEM-related fields [5],[8]. The industrial revolution will not sustain itself unless the education system is revolutionised just as vigorously.

The strengths of Arduino as a microcontroller suitable for educational purposes have been widely reported. A series of projects for physics education at the introductory level has been documented [9]. At the tertiary level, educational physics laboratory experiments have a specific experimental design for the apparatus to be deemed suitable. Ideally, the setup measures one variable after the manipulation of another variable in one round of experimentation. From this design, the theoretical relationship can be confirmed with the mathematically expressed variables measured using the laboratory setups. Arduino

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microcontrollers have also been reported and used successfully in physics laboratory applications [10],[11]. Because Arduino excels at bridging data acquisition and data visualisation, various measuring tools have also been developed for the teaching of non-physics courses. The examples are summarised in Table 1.

The development of commercially available pedagogical tools that arise from interdisciplinary fields has been so extensive that work by Catlin et al. (2019) attempts to categorise them [12]. When the tools are poorly categorized, teaching goals become unattainable. Based on their listed criteria, this phototactic device easily passed as EduRobot described by their proposed characteristics of EduRobot i.e., by having locomotion, power, command and control, communication, sensors, outputs, architecture, programming, modularity, and morphology.

In this paper, we report on a phototactic device that is programmable using an Arduino UNO microcontroller to simulate the workings of a solar tracker. A solar tracker is a feature found in a solar panel that maximises the absorption of solar energy by tracking the movement of the sun [2]. The Arduino microcontroller opens up the prospect for the construction of a solar tracker at a smaller scale, suitable for research and educational activities. A solar tracker proves to be an interesting area of research because of its feasibility with the use of an Arduino microcontroller and IDE interface. The constructed model uses light-sensitive sensors to generate input signals that determine the position of a servo, DC motor, or stepper motor as its output. The positions defined are limited to left, right, up, and down because the state of the outputs relies on logic that compares two values from two sensors. In this work, we report on a phototactic device whose angle of tilting and panning are defined through calculation incorporated within the program. Separated from the adjustable mounting plane, a sundial unit was placed in a fixed location near it.

Table 1. Arduino-based teaching tools developed between 2017 and 2020

Year	Subject/ Course	Syllabus	Applied scientific skills	Reference
2017	Biophysics instrumentation	EMG signal analysis and ECG signal analysis.	Biomedical signal processing and analysis from the electrophysiology of the heart and muscle	[13]
2019	Biophysics instrumentation	The principles of color mixing and light penetration through biological samples	Laboratory techniques	[14]
2019	Physics	Temperature dependence of electrical resistance	Data collection, processing, and visualization	[15]
2019	Chemistry	Carbon dioxide fountain	Coding, construct and demonstrate the carbon dioxide fountain phenomenon	[16]
2019	Chemistry	Measuring carbon dioxide concentration	Introductory chemistry	[17]
2020	Physics	The composition of the atmosphere	Constructing a weather station, measuring atmospheric characteristics	[18]
2020	Instrumentation	Separation technique	Constructing a microcentrifuge system	[19]
2020	Chemistry	Calorimeter	Data acquisition from a thermochemical reaction	[20]

Table 2 shows the similarities and differences of Arduino-based solar trackers found in the literature. Common components are a light-dependent resistor (LDR), a microservo, and an Arduino Uno. All projects aimed to create a solar tracker that efficiently captured solar energy through effective panel positioning while keeping construction costs to a minimum. While a higher relative efficiency is always reported for solar panels equipped with a tracking system, the method of tracking is not always clearly described, making it unfit for teaching purposes. Despite its potential usage as Educational Robot, the teaching delivery must be studied carefully designed. The criteria of a good module in STEM education were reported in the work of Zainal et al. (2018). By combining the simplicity of the Arduino system and the adaptation of a solar tracker, the development of the phototactic device stands to fit the given criteria that, when in use, the learning process becomes more interactive, intuitive, hands-on, and relatable in both classroom and outside classroom settings [5].

Table 2. Comparisons of solar-tracking device built using Arduino platform between 2016 and 2020

Axis	Arduino board	Pan & tilting mechanism	Sundial design	Reference
Dual	UNO	Controlled by a stepper motor with DM542 driver and a linear actuator.	Relying on four photodiode sensors. Sensors are clustered and placed at the zenith of the panel.	[21]
Dual	UNO	Controlled by two DC motors with L2930 driver.	Relying on four light-dependent resistors.	[1]
Dual	UNO	Controlled by two servo motors.	Relying on four light-dependent resistors.	[22]
Dual	UNO	Controlled by two servo motors.	Relying on five light-dependent resistors.	[23]
Dual	UNO	Controlled by two servo motors i.e servomotor MG996R (pan), servomotor SG90 (tilt).	Relying on four light-dependent resistors. Sensors are located at the four corners of panel.	[24]
Dual	UNO	Controlled by two servo motors.	Relying on three light-dependent resistors. Sensors are clustered.	[25]

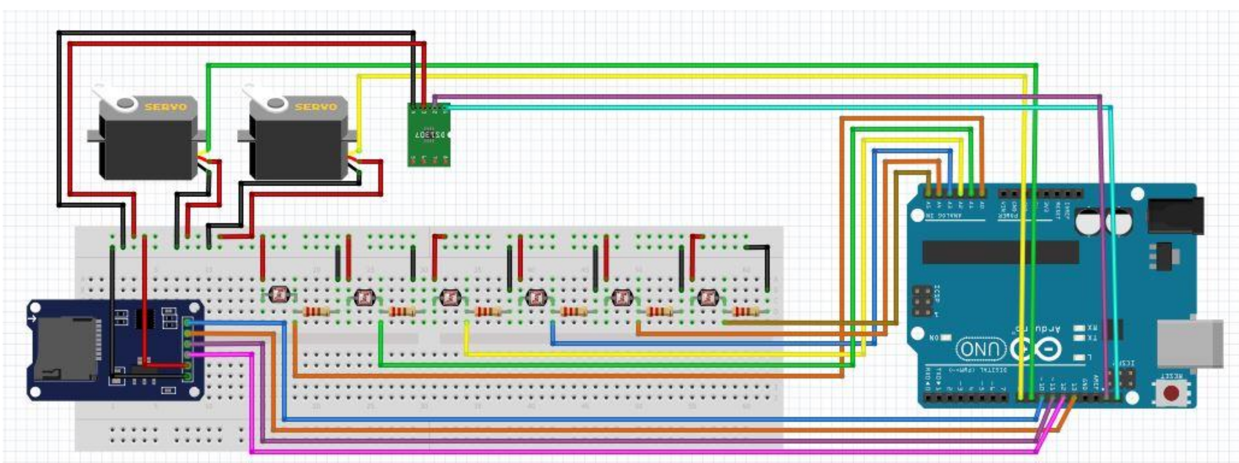

Figure 1. The schematics illustrates the combination of sundial unit, sensors located on fixed and tracker setups, dual axis controlling servos, real-time clock, MicroSD module and an Arduino UNO.

Table 3. Components and their corresponding model

Component	Model
Arduino UNO	16Mhz ATmega328
Microservo	SG90
Light-dependent resistor	
Resistor	10k ohm
Real-time Clock	RTC 1307 module
MicroSD card module	By Adafruit

MATERIALS AND METHODOLOGY

Hardware Assembly and Arduino Sketch

The hardware used in this study are shown in Figure 1 and the list of components used are shown in Table 3. The highlight of this study is the determination of tilt angle and pan angle of the device constructed. The calculations applied in the Arduino sketch are shown in Figure 2. The analog signals from A0, A1, A2 and A3 sensors that were placed on the sundial provides measured quantities in the range of 0-1023. These quantities are defined in the program as integers which are then sequentially converted to floats. To position the x-axis servo, the analog values from the A0 and A1 were summed and normalized against 700, an arbitrary value. To position the y-axis servo, float values from the A2 and A3 were normalized against A2 (float value). Both values were computed into inverse tangent function to obtain angles for the servos. The location of A4 is shown Figure 6 and had its light capturing side on the equal plane of the sundial. A5 had its light capturing side transposed according to the position of x-axis servo (θ_X) and y-axis servo (θ_Y). The θ_X range was between 0^o and 45^o while the θ_Y was between 0^o and 90^o.

Another two sensors were placed on the transverse plane of the dual-axis solar tracker and static solar panel. They were read of as input from A4 and A5. Data for comparative analysis were acquired via these pins.

Servos of the x-axis and y-axis were connected to the digital pin-8 and pin-9. The clock module was connected to the SCL and the SDA pins of the Arduino board while SD-card modules were connected to digital pins numbered 10-13. The connections of the RTC clock module and the SD-card module were adapted from sketches in Arduino C.C. library.

For data analysis, the program was written in a way that date and time (hour, minute, second), string values from A0-A5, position of x-axis and y-axis servos were recorded in the SD card. An 8GB micro-SD card was used in this study. The data was logged as .txt file before curated in an excel spreadsheet.

Sensor Calibration

Sensors were calibrated by creating a voltage divider while connecting in serial the individual sensor to 10k ohm resistor. The sensors were subjected to a common light source and the input signals were recorded. Sensors with outstanding readings were replaced with the ones of similar signal range. Outstanding readings were identified by generating a boxplot. The best six LDR were selected for the study.

Measuring Independent and Dependent Variables

The sundial comprised of four LDRs. Independent variables were measured through these sensors. Dependent variables were the angles of the servos and light signals captured from LDR on the transverse plane and the LDR on the phototactic panel.

The experimental setup is shown in Figure 4. Artificial light fixture was used in placed of natural sunlight. It was constructed from addressable LED strip that shift out from 0^o to 180^o through a semi-elliptical path suspended above the setup, controlled using shift-out function using another unit of Arduino Uno microcontroller. Data collected and shown in this study was obtained from 14.6 minutes of shift out period.

Data Collection and Analysis

Statistical analysis i.e. t-test was performed using online statistical calculator to compare data sets obtained from A4 and A5 sensors.

```
int sensorValue = analogRead(A0);
int sensorValue2 = analogRead(A1);
int sensorValue3 = analogRead(A2);
int sensorValue4 = analogRead(A3);
float voltagez = sensorValue3 * (5.0 / 1023.0);
float voltage4 = sensorValue4 * (5.0 / 1023.0);
float sumxy = sensorValue + sensorValue2;
float ratiozz = voltagez / voltagez;
float ratio4z = voltage4 / voltagez;
int thetax = atan2 (sumxy,700) * 180/3.14159265;
int thetay = atan2 (ratio4z,ratiozz) * 180/3.14159265;
pos1 = map(thetax, 0, 90, 5, 50);
pos2 = map(thetay, 0, 90, 5, 95);
```

Figure 2. Arduino sketch that defines the servo position based on inputs from four sensors.

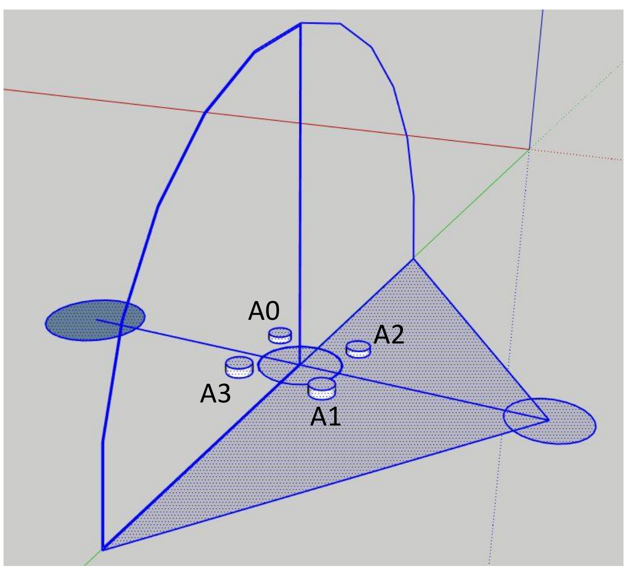

Figure 3. Sundial unit that feeds signals into the program. It consists of two pairs of LDRs (A0, A2; A1, A3) that are separated by an opaque divider.

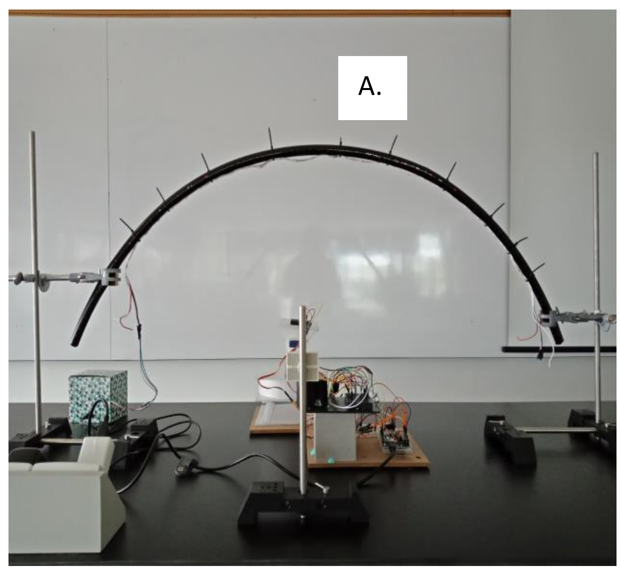

Figure 4. The side view of the experimental setup. A. the elliptical path of the artificial light used in this study.

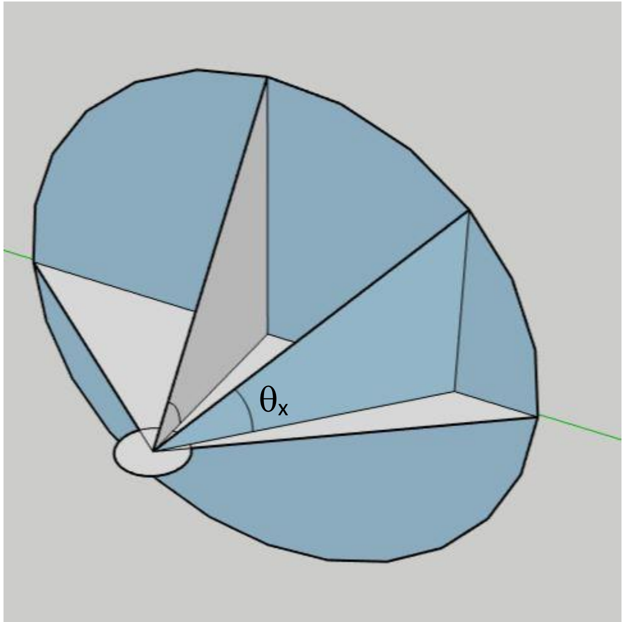

Figure 5. The position of θ_X is given by

$$\tan^{-1}(\frac{A0+A1}{700}).$$

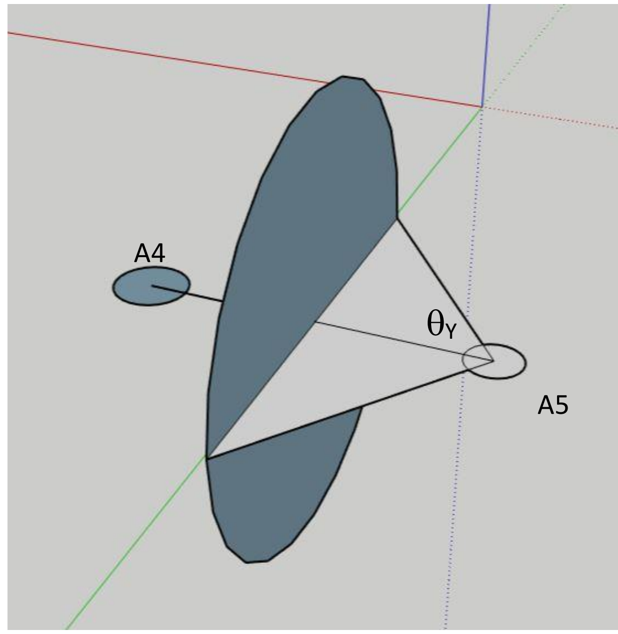

Figure 6. The position of θ_Y is given by

$$\tan^{-1}(\frac{A2}{A3}/\frac{A3}{A3}).$$

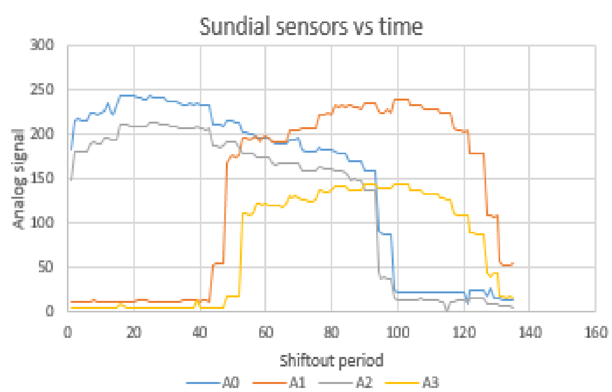

Figure 7a. Signals from sundial (A0-A3) against shift out period.

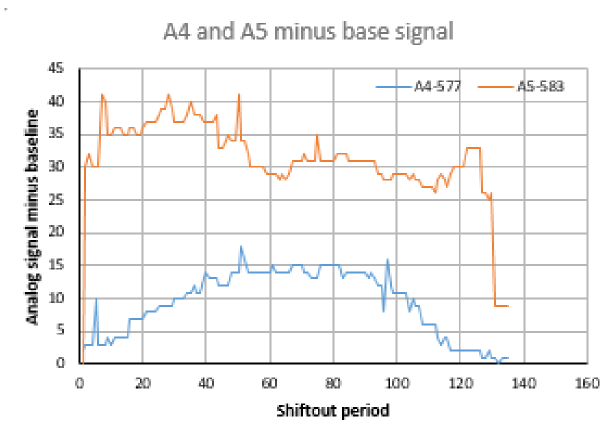

Figure 7b. A4 and A5 signals minus their respective baseline against shift out period.

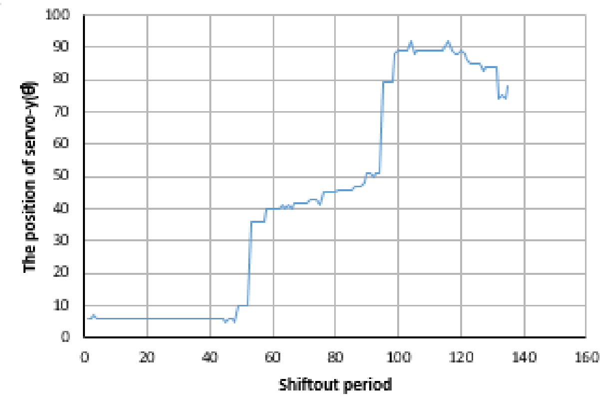

Figure 8. Ideally, across the shift out period, the position of y-axis servo changes from 5° to 95°.

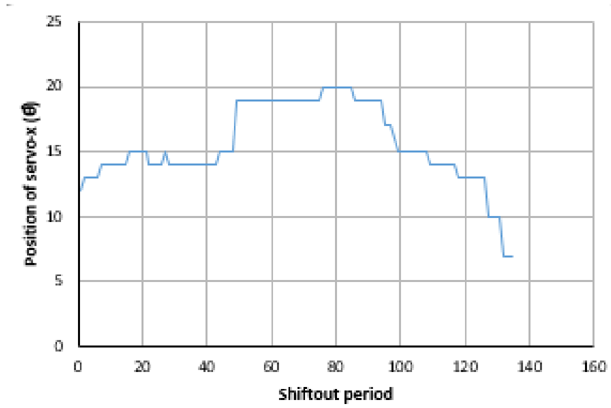

Figure 9. Ideally, across the shift out period, the position of x-axis servo changes from 5° to 50° to 5°.

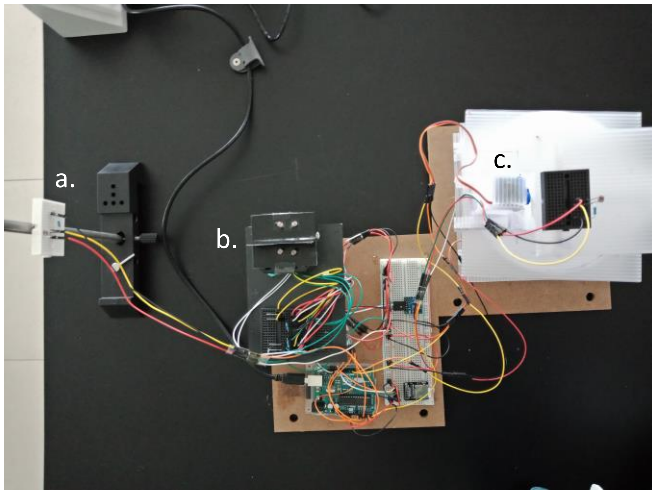

Figure 10. Top view of the setup. a. A4 LDR; b. sundial unit made of A0-A3; c. A5 LDR on a moving platform controlled by servo-x and servo-y .

RESULTS AND DISCUSSION

The input signals from the A4 LDR located on a fixed position (M=4.92, SD=9.33) compared to the input signals from the A5 LDR located on the tracker (M=31.16, SD=6.41) demonstrated a significant score of $t(134) = -31.4$, $p<0.05$.

The shift out period was taken from hour 3:23:11 to hour 3:37:45 according to the RTC module used. There are 135 data registered allowing 6.5 seconds delay between two registered data.

The sensors on the sundial received two phases of exposure i.e., dark phase and light-exposed phase. Signals from A0 and A2 shown in Figure 7a confirm that they were located on the same side of the sundial and were the first exposed to the light source.

Across the shift out period, servo-y and servo-x showed non-smooth transitions. However, the transition between angles 5° and 95° can be seen clearly in Figure 8 and Figure 9 as intended in the Arduino sketch.

Huang (2015) has described the foundations of Arduino application in an introductory physics laboratory in physics education [9]. Among others, his work promotes the use of Arduino Uno as a simplified measuring instrument that converts electrical signals from sensors into measurable units of voltage. Reported in this paper is a work that extends the use of the received inputs from sensors by feeding the values into a trigonometric function that determines the deflection angles of the solar tracker. This supports project-based learning by demonstrating the concepts of coding and robotics.

The use of Arduino offers real-time data display when a serial plotter is used. In this work, however, the circuit is made independent by incorporating the use of a micro-SD card to store the collected data. This was done to simulate the need for a solar tracker to be an independent unit. The data acquisition method can be improved further by using an internet shield to enable wireless communication between the tracker unit and the Arduino IDE. The material used to construct the model can also be improved by 3D printing it.

Because of the two types of mounting of the solar panel used, there are two types of data that can be gathered, i.e., light intensity data from a static solar panel and light intensity data from a light-responsive panel. These two types of data offer a way to demonstrate the application of statistical analysis in the physics laboratory. In this work, a t-test was employed to distinguish data sets generated from an instrument that was optimised from one that was not optimized. The variables can also be plotted against a time variable to display a time plot. A single experiment can be used to develop a variety of practical laboratory skills. Admittedly, the steep learning curve to construct an Arduino-based experiment setup and the need for 3D-printed modelling may hinder the wide use of such a setup. However, there is a large community that can offer technical support to those who are using the Arduino microcontrollers, including academic providers who are moving from conventional laboratory practises to project-based learning. The learning curve proves to be a temporary stage once the basics are mastered.

CONCLUSION

The various approaches that can be used to implement the device demonstrate its versatility. Using this setup, learners are presented with options to delve into the programming aspects of the setup, including performing comparative analysis given two sets of independent data sets, the application of trigonometric functions in the context of the actual world, and data visualizations.

In the future, the attitudes of educators from various backgrounds toward the use of phototactic device in relevant subjects can be investigated. By tuning the level of complexity of the module, the setup can also be used to study the students' attitudes towards STEM subjects. The device and its complementing teaching modules may be a good candidate for design and developmental research (DDR) to customise its functionality based on the targeted audience.

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