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Arduino-based infrared power meter for use with a Leslie cube

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Abstract
This article presents the design and fabrication of an infrared power meter, based on an Arduino Nano and an MLX90614 sensor, intended to be used by school students to carry out the required practical investigating the emission of infrared radiation from different surfaces using a Leslie cube. Results of testing demonstrate that when the Leslie cube is at a temperature of 81 °C, the matt black surface emits 497 W m^{-2}, while the shiny metal surface emits only 57 W m^{-2}. With a low material cost of around $40 and straightforward assembly, this device offers a practical solution for schools. Additionally, it can be easily adapted for other purposes, such as temperature data logging.

Keywords: physics education, infrared power meter, Leslie cube, STEM education, Arduino

Supplementary material for this article is available online

1. Introduction

Investigating the amount of infrared radiation (IR) emitted by different surfaces using a Leslie cube [1] and an infrared detector is one of the core physics GCSE practicals required by the two largest exam boards in the UK, AQA and Pearsons Edexcel [2, 3]. In 2022–23, these exam boards combined awarded over 87% of GCSE qualifications [4].

A Leslie cube is a cubic metal vessel that can be filled with hot water (e.g. from a recently boiled kettle). The four outward-facing sides of the Leslie cube have different finishes: usually shiny black, matt black, shiny metallic and matt white. The aim of the experiment is to compare the

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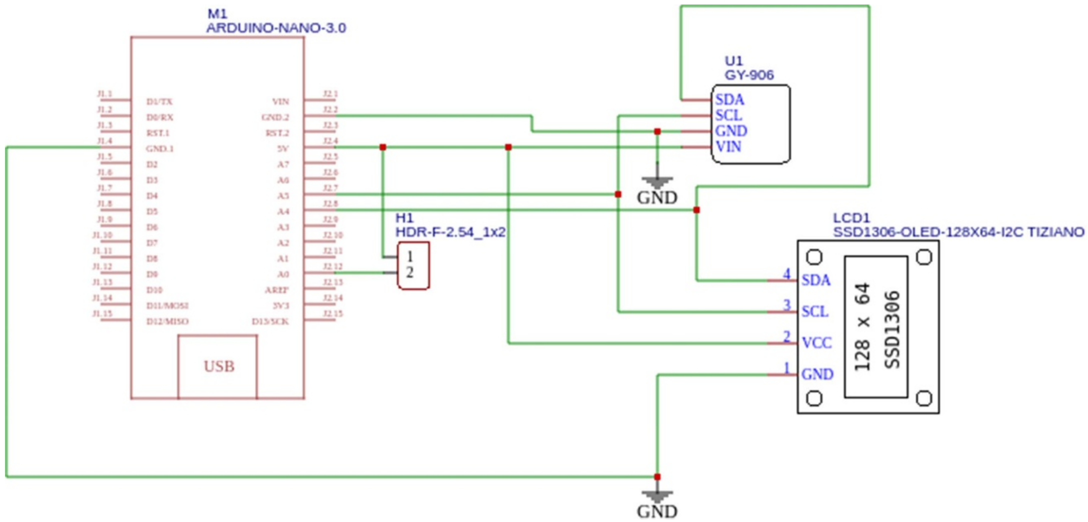

Figure 1. Schematic showing how the components of the infrared power meter were connected together.

IR emitted from the different surfaces. This experiment can be challenging to conduct with an entire class because a full set of infrared sensors and data loggers can be costly, so it is often demonstrated by the teacher instead.

This paper describes the design and fabrication of a cost-effective, Arduino-based infrared power meter for use with a Leslie cube. A similar design was built and tested by Garcia *et al* [5]. Their device was designed primarily for automated data acquisition using a PC. In contrast, our device is optimized for classroom use with a Leslie cube as part of a class set, enabling students to perform the required practical individually or in small groups. Additionally, our standalone device is USB-powered and features an integrated display, thereby removing the need for a PC or laptop: an expensive resource that may be vulnerable in a classroom setting, particularly when students are working with hot water.

2. Infrared power meter design

2.1. Hardware

The infrared power meter was designed and built around a Melexis MLX90614 infrared thermometer [6], which measures object temperatures in the range of $-70\,^{\circ}$C to $380\,^{\circ}$C by detecting IR in the $5.5\,\mu$m–$14\,\mu$m wavelength range, and an Arduino Nano microcontroller [7], which performs the necessary calculations and displays the results on a SSD1306 organic light-emitting diode (OLED) screen [8]. Both the MLX90614 sensor and the SSD1306 display communicate with the Arduino via the I2C bus [9]. These three components were connected as shown in figure 1 and mounted on a custom-made printed circuit board (PCB). Figure 2 shows the top side of the PCB design, along with a picture of a fully populated board. The PCB was housed in a 3D-printed enclosure. The device was powered via a 5 V USB cable, and the total bill of materials (BOM) was approximately $40.

2.2. Software

Figure 3 shows the code that was uploaded to the Arduino. This code reads the temperature data from the MLX90614 sensor and displays the measured object temperature and irradiance on the OLED screen. It also transmits the same data, along with the ambient temperature measured by the MLX90614's on-board sensor, to the serial port for monitoring on a PC if connected. Since the MLX90614 sensor does not directly report irradiance (I), it was necessary to calculate it on the Arduino using the measured object temperature (T) and the Stefan–Boltzmann equation [10]:

$$I = \sigma\epsilon\left(T^4 - T_0^4\right) \qquad (1)$$

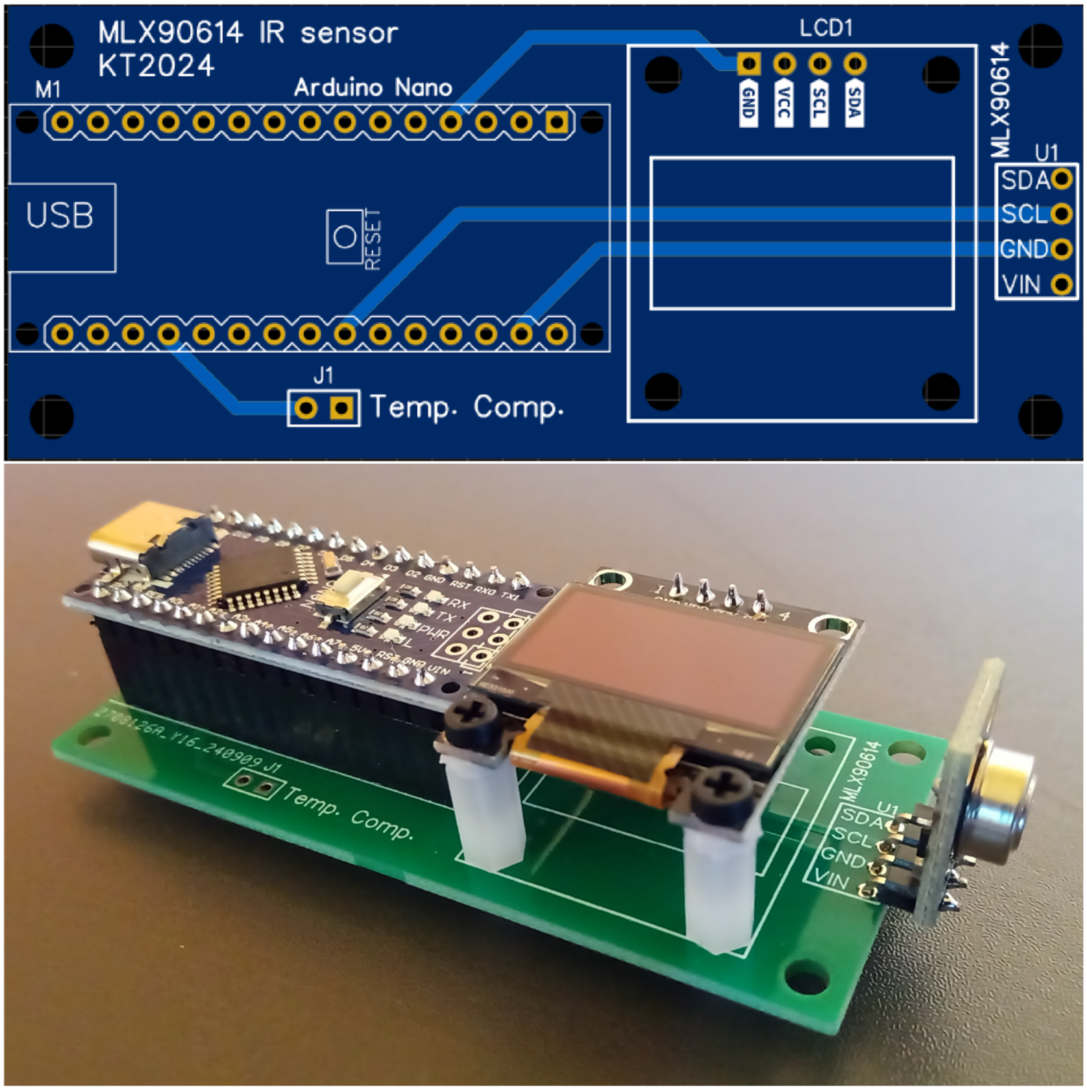

Figure 2. Printed circuit board design and populated PCB.

where σ is the Stefan–Boltzmann constant ($5.670\,374\,419 \times 10^{-8}\,\mathrm{W\,m^{-2}K^{-4}}$), ϵ is the emissivity and T_0 is ambient temperature. Initially it was considered that T_0 could be measured by the MLX90614's on-board sensor. However, during preliminary testing, it became clear that when the device was placed near a Leslie cube filled with hot water, the proximity caused the sensor to heat up, resulting in misleading T_0 readings. To resolve this, a fixed T_0 of 20 °C was used in the Arduino code. Since the default emissivity value used by the MLX90614 sensor [6] is 1, this same value was applied in the code.

3. Experimental setup

The infrared power meter was tested using a Leslie cube with a side length of 100 mm. The experimental setup and a close up of the power meter are shown in figure 4. The cube had four surfaces with different finishes: shiny metal, matt black, shiny black, and shiny white. A 3D printed stand held

```
// Libraries
  #include <Adafruit_MLX90614.h>
  #include <math.h>
  #include <Wire.h>
  #include <Adafruit_GFX.h>
  #include <Adafruit_SSD1306.h>
  #include <Adafruit_Sensor.h>
  #define SCREEN_WIDTH 128 // OLED display width, in pixels
  #define SCREEN_HEIGHT 64 // OLED display height, in pixels
// Declaration for MLX90614 and SSD1306 display connected to I2C pins
  Adafruit_SSD1306 display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire, -1);
  Adafruit_MLX90614 mlx = Adafruit_MLX90614();
// Variables
  float ToC; // Object temperatue in C
  float ToK; // Object temperatue in K
  float TaC; // Ambient temperatue in C
  float sigma = 5.670374419e-8; // Stefan-Boltzmann constant

void setup() {
 Serial.begin(9600); // Set up serial comumication

// Set up MLX90614
  if (!mlx.begin()) {
    Serial.println("Error connecting to MLX sensor. Check wiring.");
    while (1);}
// Set up OLED display
  if(!display.begin(SSD1306_SWITCHCAPVCC, 0x3C)) {
    Serial.println(F("SSD1306 allocation failed"));
    while (1);}
  delay(2000);
  display.clearDisplay(); // Clear display
  display.setTextColor(WHITE);} // Yellow in this case

void loop() {
// Get temperatures and do calculations
  ToC = mlx.readObjectTempC(); // Read object temperature
  TaC = mlx.readAmbientTempC(); // Read ambient temperature
  ToK = ToC + 273.15; // Convert to Kelvin
  float M = sigma * (pow(ToK,4)- pow(293.15,4)); // Calculate Irradiance
// Display results on OLED
  display.clearDisplay(); //clear display
// Display object temperature
  display.setTextSize(1); display.setCursor(0,0); display.print("Temperature: ");
  display.setTextSize(2); display.setCursor(0,10); display.print(ToC); display.print(" ");
  display.setTextSize(1); display.cp437(true); display.write(167);
  display.setTextSize(2); display.print("C");
// Display Irradiance
  display.setTextSize(1); display.setCursor(0, 35); display.print("Irradiance: ");
  display.setTextSize(2); display.setCursor(0, 45); display.print(M,1);
  display.setCursor(70, 45); display.print("W/m"); display.setTextSize(1); display.setCursor
      (108, 42); display.print("2");
  display.display(); // Display message on screen
// Print data to serial port also
  Serial.print("Ambient = "); Serial.print(TaC);
  Serial.print("*C\tObject = "); Serial.print(ToC); Serial.print("*C\tIrradiance = ");
  Serial.print(M); Serial.println(" W/m^2");
  Serial.println();
  delay(1000);} // Repeat every 1 s
```

Figure 3. Arduino code.

the power meter centrally 40 mm in front of the cube to ensure that the face of the cube completely filled the 90° field of view of the MLX90614 sensor. The cube was filled with hot water from a freshly boiled kettle, and the power meter was placed in front of each surface in turn. For each surface, the irradiance, object and ambient temperatures, and the temperature of the water inside the cube were recorded. The water temperature was measured using an alcohol thermometer, with

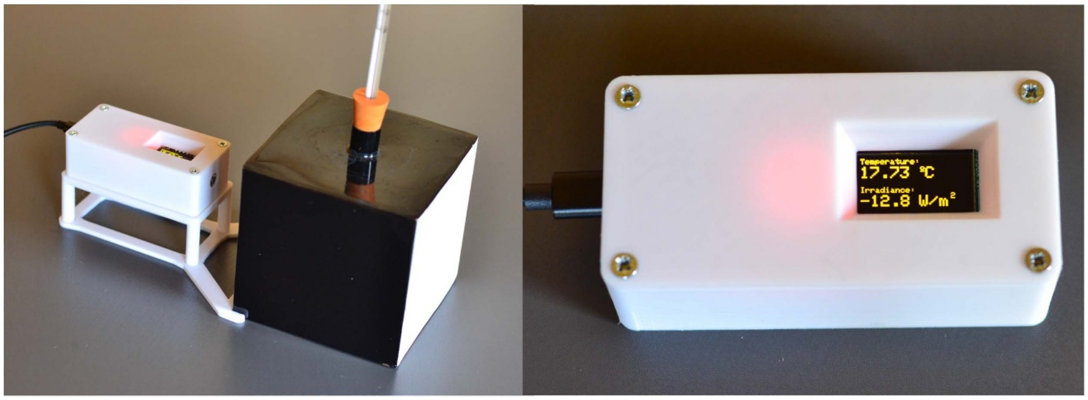

Figure 4. Experimental set up with a 100 mm Leslie cube and close up of the IR power meter.

Table 1. Results with the IR power meter 40 mm away from a Leslie cube of side length 100 mm. The ambient temperature (T_0) and the object temperature (T) were measured by the power meter, and the temperature of the water in the cube (T_C) measured with an alcohol thermometer. Note that T_0 was fixed was at 20 °C in the calculation of I.

Surface	T_0 (°C)	T(°C)	I (W m^{-2})	T_C (°C)
Shiny metal	21.5	29.5	57	81
Matt black	21.8	83.4	497	81
Shiny black	22.4	80.9	471	81
Shiny white	22.9	81.7	479	81

the bulb positioned roughly at the center of the cube.

4. Results and discussion

The results of the measurements described in section 3 are reported in table 1 and shown graphically in figure 5. The results clearly demonstrate differences in the intensity of IR emitted by the various surfaces. The matt black surface emitted nearly nine times as much energy per second as the shiny metal surface. The differences between the painted surfaces were less pronounced. As expected, the matt black surface emitted the most IR, followed closely by the shiny black and shiny white surfaces. Interestingly, the shiny white surface emitted slightly more radiation than the shiny black surface. This result is surprising, as the white surface would typically be expected to emit less radiation than the black one. The small difference may be partly due to variations in the roughness of the two surfaces.

5. Conclusions

We have successfully designed and built an infrared power meter based on an Arduino Nano and an MLX90614 sensor, specifically intended for classroom use to investigate the IR emitted by different surfaces of a Leslie cube. The results show that the device is highly effective for this purpose, with a matt black surface emitting nearly nine times the radiation of a shiny metal one.

The total BOM for the power meter is approximately $40. This, combined with the simple fabrication process, requiring only access to a 3D printer and basic soldering skills, makes it an affordable and practical device for schools. Its Arduino-based design adds versatility, as it can be powered by 5 V via a USB battery bank or connected to a PC for data logging through the Arduino's serial port. The Arduino code is also easily updatable, allowing adjustments to the data acquisition rate or other parameters as needed. To facilitate replication of our device, all necessary files are provided as supplementary data.

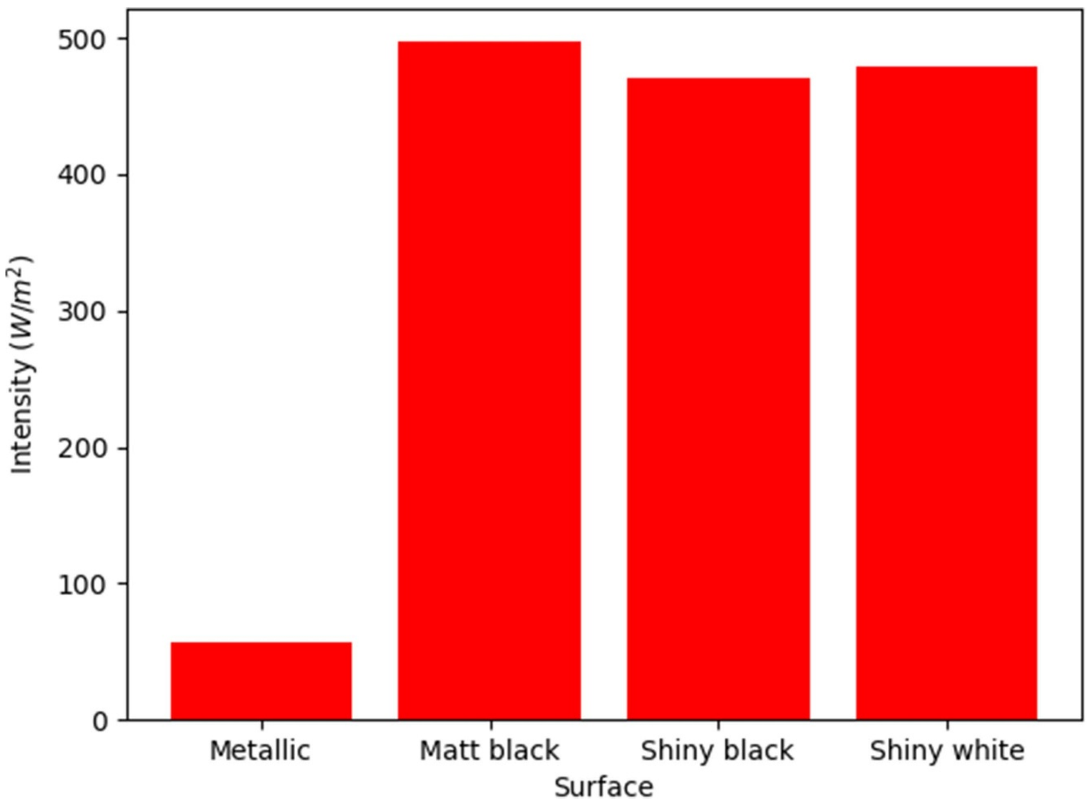

Figure 5. Histogram showing the results from table 1 obtained with the IR power meter 40 mm from the Leslie cube.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Olson R G 1969 A note on Leslie's cube in the study of radiant heat *Ann. Sci.* **25** 203–8
[2] AQA 2018 GCSE physics core practicals handbook (available at: https://filestore.aqa.org.uk/resources/physics/AQA-8463-PRACTICALS-HB.PDF) (Accessed 19 November 2024)
[3] Edexcel 2016 GCSE 9-1 sciences core practical guide (available at: https://qualifications.pearson.com/content/dam/pdf/GCSE/Science/2016/teaching-and-learning-materials/gcse-9-1-sciences-core-practical-guide.pdf) (Accessed 19 November 2024)
[4] Ofqual 2023 Annual qualifications market report: 2022 to 2023 academic year (available at: https://www.gov.uk/government/statistics/annual-qualifications-market-report-academic-year-2022-to-2023/annual-qualifications-market-report-2022-to-2023-academic-year) (Accessed 15 November 2024)
[5] Garcia E M, Goncalves A M B and Calheiro L B 2023 Leslie's 'can' using arduino *Phys. Educ.* **58** 033004
[6] Melexis 2019 MLX90614 family datasheet: single and dual zone infra red thermometer in TO-39 (Rev. 13)

[7] Atmel Corporation 2015 ATmega328P datasheet (Rev. 7810D-AVR-01/15)
[8] Solomon Systech 2009 SSD1306 advance information: 128 x 64 dot matrix OLED/PLED segment/common driver with controller (Rev. 0.4.)
[9] NXP Semiconductors 2021 I^2C-bus specification and user manual (Rev. 7.0.)
[10] Wyatt C L 1978 *Radiometric Calibration: Theory and Methods* (Academic) ch 4, pp 29–37

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