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Raspberry Pi multispectral imaging camera system (PiMICS): A low-cost, skills-based physics educational tool

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Here, we report on a skills-building 3D-printable, Raspberry Pi-based multispectral camera (15–25 spectral channels in the visible and near-IR) for as little as \$150–\$300. The cameras rely on measuring the reflectance spectra of various objects using both active and passive illumination. The cameras were used in a successful pilot program designed such that students could learn 3D modeling, 3D printing, feedback, control, image analysis, Python programming, systems integration, and machine learning, as well as spectroscopy. The students in the pilot program studied a wide array of target spectra upon completion of their cameras, showing their aid as valuable research tools. We believe this can be an important instructional tool in introductory or advanced STEM laboratory courses. © 2026 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

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I. INTRODUCTION

Multispectral and hyperspectral imaging are critical diagnostic tools in precision agriculture, medicine, recycling, environmental monitoring, defense, and quality control.^{1–12} Multispectral cameras usually have between two and ten color channels and capture spectra within each of those specific bands, while hyperspectral cameras typically have hundreds or even thousands of color channels and measure a continuous spectrum at each pixel in an image. Unfortunately, commercial multispectral and hyperspectral imaging systems are out of the price range of most instructional laboratory programs, including those in developing countries.

Here, we report on a pilot program administered from Chapman University to students in the National Polytechnical School of Quito Ecuador, the University of Pretoria and Stellenbosch University in South Africa, and Chapman University in Orange California in which students were given the opportunity to build and then use multispectral cameras.

The students in our program were citizens of several developing countries and ranged from first-year undergraduates to postdoctoral researchers. A primary motivation for building the multispectral cameras was to aid in precision agricultural advancements^{7,10} (such as detection of water stress, plant disease, and nitrate and nitrite concentrations) in the students' respective countries.

While building affordable LED-based multispectral imaging camera systems is not new,^{13,14} here we focus on providing a low-cost, skills-building teaching framework that, upon completion, equips students with the ability to perform fundamental research tasks.

The multispectral imaging cameras are based on a Raspberry Pi, the inexpensive, small form factor, lightweight single-board computer. The Raspberry Pi has a camera serial interface that can directly connect to a range of economical high-resolution cameras; in this project, we used the Raspberry Pi Module 3 whose optical responsivity ranges from wavelengths less than 400 nm to greater than 1000 nm. The Pi controls the camera, LEDs, and motors, as well as

performs image processing and machine learning. During the construction process, students acquire experience in the areas of 3D modeling, 3D printing, systems integration, soldering, electronics, Python programming, image analysis, and optical spectroscopy.

An aim of our pilot program was not to follow a single prescribed research path but to provide a learning framework in which creativity and curiosity could drive the work. As a result, many cameras were built during the pilot, and the reflectance spectra of many different objects were studied. Students were tasked with choosing a research topic based on a literature search and then designing, building, and coding a purpose-built camera. After that, they acquired and analyzed the spectra emitted by their materials or objects of choice.

There are several fundamental physics principles, in addition to the important laboratory skills that can be taught during this project. At a basic level, the students can learn about waves, wavelength, frequency, speed of light, diffuse and specular reflection. More advanced topics can include the optical and infrared spectrum, detector responsivity, spectral filtering, materials properties, dark current, noise and spectroscopy.

In what follows, we give a high-level overview of a general-purpose Raspberry Pi multispectral imaging camera system (PiMICS) and its use in acquiring reflectance spectra. As a specific example, we demonstrate how the PiMICS can be used to measuring the time-dependent ripeness of a banana. We also provide a brief report of student engagement as well as a list of parts with their associated costs. For much further detail about the program, circuit design, camera construction, best practices, and lessons learned during the project, see the [supplementary material](#).

II. EXAMPLE CAMERA

While as many as ten cameras of varying designs were built during the pilot, we give, as an example, an overview of an LED-only device (shown in Fig. 1 and an earlier version used in the experiments shown in Fig. 2). This system is a general-purpose multispectral camera. Within this device, there are 15 3-W surface-mount-design (SMD) chip-on-board (COB) LEDs, which are controlled by Raspberry Pi's general-purpose input/output (GPIO) pins. The COB SMD

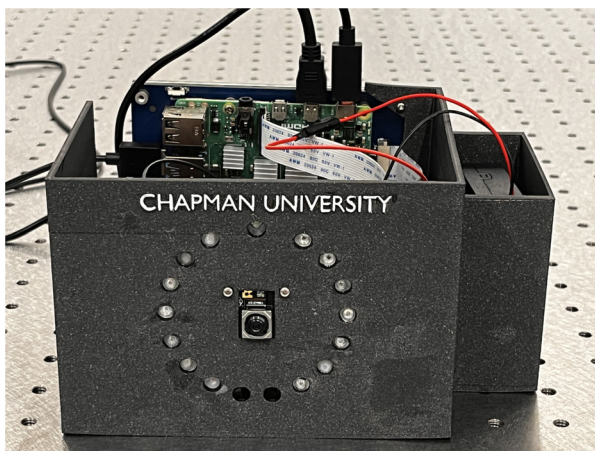


Fig. 1. Front view of the basic camera with LED-only illumination. The camera has 15 high-powered LEDs for active illumination.

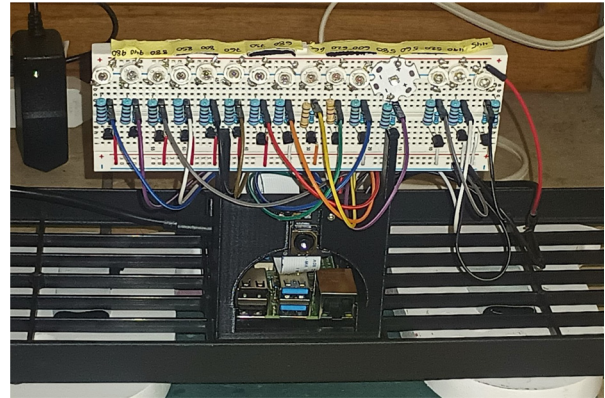


Fig. 2. An early version of the basic PiMICS model used in experiments.

LEDs were chosen because of their luminosity, wide emission angle, and uniform illumination. In units of nanometers, the peak LED wavelengths (measured using a spectrometer) are 439, 498, 535, 560, 592, 598, 621, 660, 681, 751, 787, 844, 877, 940, and 978. The spectral widths of these LEDs tended to be of the order of 10 nm at the short wavelengths and progressively increased to a few tens of nanometer at the large wavelengths.

The camera body was designed using Blender and 3D printed. The camera body incorporates a 4-inch monitor on the back, allowing the user to run programs, process data, and view images even while offline. There is a 30-W 10 000-mAh power bank that can run the camera for many hours (≈ 6 h depending on use). For more information on the power sources, Raspberry Pi features, LED circuits, camera features, setup, and an experimental example, see the [supplementary material](#).

An experimental schematic of the system is shown in Fig. 3. One by one, each LED is turned on in order to illuminate a sample and Teflon reference target, the reflected light from the object and reference is imaged by the camera, and then the LED is turned off. After acquiring images of the reflection under illumination by each of the LEDs, a composite image of relative intensities is created. Also, regions of interest on the object and Teflon reference target are averaged to give higher signal-to-noise ratios.

Example spectral images with different illuminating LEDs are shown in Figs. 4 and 5 of an apple. The apple is barely visible when illuminated by 445 nm light, but has moderate reflectivity at 596 nm. The light from the reference Teflon is averaged within the white box shown in the figure and compared to each pixel of the apple.

III. STUDENT ENGAGEMENT AND CHOICE

The students involved in our pilot program were volunteers from several different countries of origin with widely varying time commitments and interests. They also had a significant range of educational experience, ranging from first-year undergraduates up to postdocs. The students were first asked to search the literature for applications of multispectral imaging. Each student or student group then chose an experiment or system they wanted to study. Next, each group designed their own camera to be incorporated in an all-in-one 3D printed package that was purpose-built for their experiment. The students used Fusion360 or

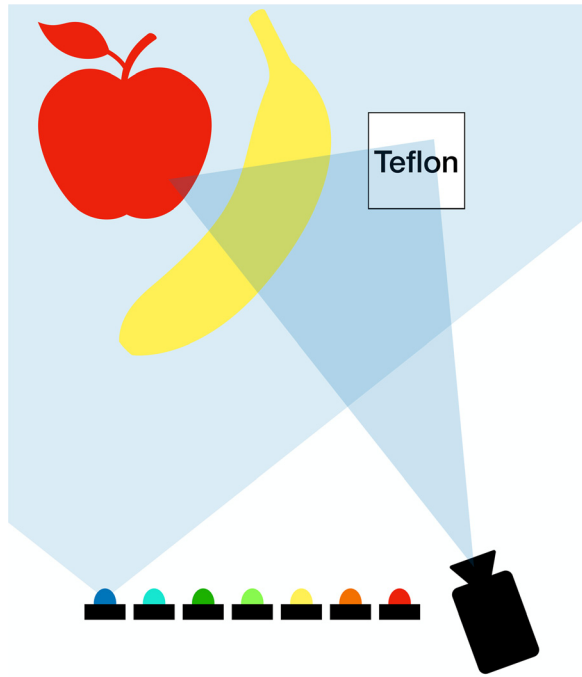


Fig. 3. An array of LEDs having different center wavelengths are illuminated one by one (not to scale). The light from each LED scatters from the object of interest (e.g., apple or banana) and a Teflon reference target. The reflected light is measured in the camera. As long as the Teflon target is close to the object of interest and the illumination is close to uniform, a high-quality reflectance spectrum can be measured.

Blender to do the 3D modeling and then 3D printed their camera bodies. Typically, students opted to work on multispectral imaging topics that were well established in the literature, such as plant health, water stress,¹⁵ or fruit ripeness (bananas,¹⁶ avocados, apples, and lemons). Several of the groups developed their own computer code, shared code, or modified code given by the instructor for their specific application. The most well-developed experiment performed by one of the student groups studied the polarization and spectral analysis of reflected light from nanostructured insect wings. This project is discussed in detail in the [supplementary material](#).



Fig. 4. An LED with center wavelength at 445 nm illuminates an apple and a Teflon reference. At 445 nm, the apple reflectance is very low and is barely visible in the image.



Fig. 5. An LED with center wavelength at 596 nm illuminates an apple and a Teflon reference. At this wavelength, the apple reflectance is about 50%.

IV. BANANA RIPENESS

Owing to its straightforward methodology and obvious impact, we show the spectral data measured over time of a ripening banana. We wrote code in Python that controlled the output of the LEDs, controlled the exposure time and gain of the camera, and performed postprocessing of the composite images using standard Python packages. Within a light-tight box, an unripe (green) banana was placed about half a meter away from the camera system; in addition, a thick rectangular piece of Teflon, a few centimeters on a side, was placed next to the banana to act as a spectral reference. The camera exposure time was set to prevent saturation but gave a sufficiently high signal-to-noise ratio. We aimed for peak pixel values on the Teflon of approximately 200 on an 8-bit scale. The code cycled the LED/camera system through the measurement process every six hours.

The spectra of a ripening banana over several days are shown in Fig. 6. This figure shows 28 spectra of the banana taken over a seven day period (four times per day).

It is illustrative to compare our results to those in Ref. 16. Several of the main features agree well. For example, a prominent feature is the change in reflectivity around 660 nm, which is the chlorophyll resonance (a resonance

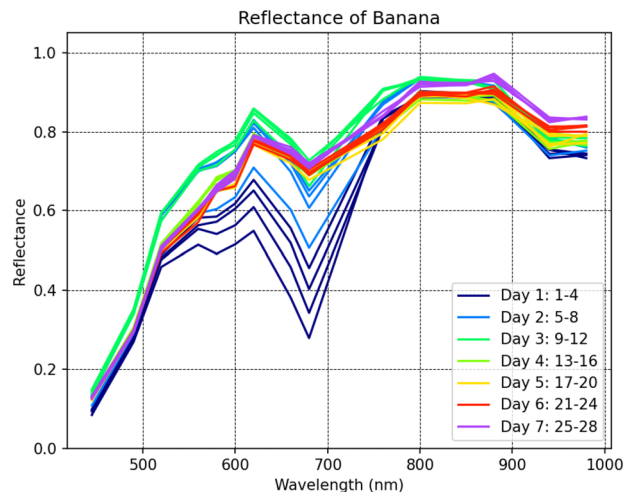


Fig. 6. Multispectral imaging experiment showing changes in the spectral skin color of a ripening banana with time.

corresponds to a dip in the reflectance spectrum). As the banana passes from green to yellow, this resonance disappears because of the breakdown of chlorophyll during the ripening process. There are also sugar and water resonances shown around 850 and 970 nm, respectively. While the gross properties of the spectra agree well with those in Ref. 16, some of the finer details, especially near the sugar and water resonances, do not match up. Further study is warranted to understand the differences. It is important to note that discrepancies between measured data and previously performed experiments can be a valuable learning experience for the students to solve problems, deeply probe their system, and understand physical concepts. It should be noted that we were not able to fully observe the water resonance, as the last LED in our array had peak emission inside the 970 nm water band. Also, the sugar band will look approximately flat (i.e., not a dip) at 850, but the reflectivity of that region will change depending on the sugar content.

V. DISCUSSION

We believe this banana experiment shows the valuable role that this inexpensive system can play in precision agriculture, but more importantly in helping students solve problems and understand spectroscopy. Interestingly, the luminosity of each LED was only a few tens of megawatt, which is about two orders of magnitude below the peak value (3 W), but detector saturation still occurred for measurements longer than 10 ms. We believe this implies that even remote measurements with distances of tens of meters away from the targets are possible, allowing for nighttime drone flyovers of agricultural areas using LEDs.

Another important point is that we believe that the reference target is perhaps not critical. Rather, in most cases, the relative brightness and pixel sensitivity can be compensated by calibrating the exposure time for each wavelength. In many cases, the experiments performed by the cameras will be to look at temporal changes in reflectance of a single object, meaning that the difference spectra rather than the absolute spectra will be critical.

VI. CONCLUSION

In conclusion, low-cost, skills-building multispectral cameras based on the Raspberry Pi were created as educational tools. We believe students who build these cameras will acquire a number of useful technical skills and be exposed to fundamental physics concepts related to optics. Importantly, we expect that this educational and outreach project will play a valuable role in developing countries where access to high-end equipment can be difficult and costs prohibitive. In addition, we believe that our open-ended project will find wide interest in developed countries where, all too often, cookbook experiments dominate the laboratory experience.

SUPPLEMENTARY MATERIAL

Please click on [this link](#) to access the supplementary material for details about the circuit. Print readers can see the supplementary material at <https://doi.org/10.60893/figshare.ajp.c.8129453>.

AUTHOR DECLARATIONS

Conflict of Interest

The authors declare that they have no conflicts to disclose.

APPENDIX: PARTS LIST

For those who wish to reproduce this camera, here is a recommended list of parts. The approximate cost for parts assume a per-cost value. For example words, it may be necessary to purchase 10 LEDs at \$6, but the per-cost price is \$0.6.

- Raspberry Pi 4b (4 GB good, 8 GB preferred), SD card flashed with Raspian, 15 W (minimum) 5 V power supply (can be battery) for Pi (\$80–\$120).
- Any HDMI-enabled monitor (\$30–\$200).
- Breadboard (solderless or solderable) for LEDs and electronics (\$2)
- Female to male Dupont wire for Raspberry Pi or Arduino (20 pieces) (\$2)
- Generic NPN transistor (we used 2N2222) (20 pieces) (\$1) (alternative: Darlington array)
- Jumper wires kit (various lengths and colors) (\$5)
- NoIR camera (we used Raspberry Pi Camera Module 3) (\$8–\$25)
- 6 V power supply for LEDs (can be battery, such as 4AA in series, or just a 6 V power supply) (\$7–\$10)
- 22 Ω 1 W resistors (20 pieces) (\$2)
- 330 Ω 1/4 W resistors (20 pieces) (2)
- 1 chip-on-board (COB), surface-mounted-design (SMD) LED at each wavelength described in the paper (\$15).
- 3D printer filament (\$3). Depending on the skill level of the student, it can take between 15 and 50 h to design, print, code, wire, and build this system. The experiment that follows can range in complexity from simple to difficult and in time from days to months.

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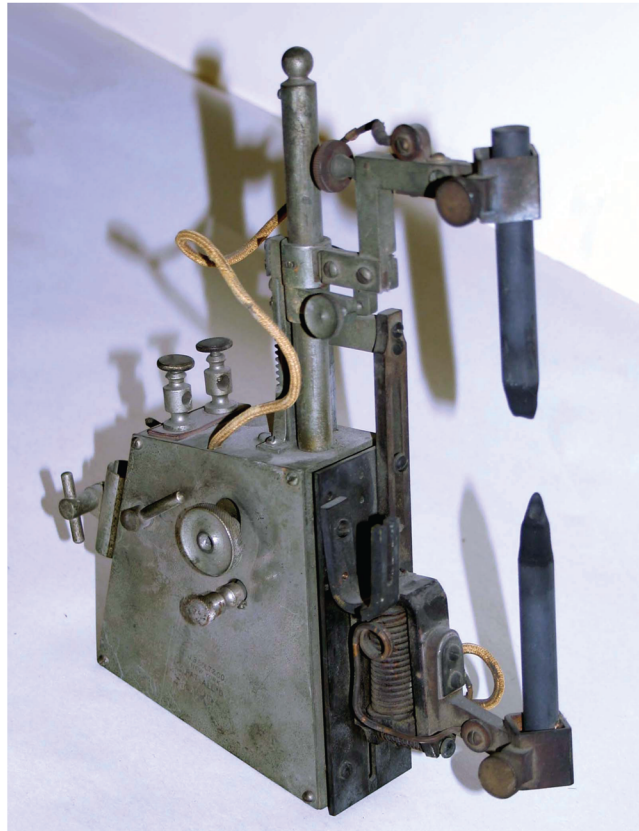
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Duboscq Carbon Arc Lamp

The carbon arc lamp produced an intense point source for use in optical demonstrations; nothing today can rival it. The shape of the ends of the electrodes – a point on one side and a cup on the other – shows that the lamp was operated on direct current. After the arc is struck, the electrodes are withdrawn to an optimum spacing, and the mechanism in the base uses a feedback loop to maintain this spacing. Duboscq was a leading French manufacturer of optical apparatus toward the end of the nineteenth century. This apparatus could be put into use once more at Washington and Lee University. (Picture and text by Thomas B. Greenslade, Jr., Kenyon College)