The Physics Teacher

PAPERS | FEBRUARY 01 2023

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Phys. Teach. 61, 133–137 (2023)
https://doi.org/10.1119/5.0066060

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An Arduino-Based Experimental Setup for Teaching Light Color Mixing, Light Intensity Detection, and Ambient Temperature Sensing

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The Arduino microcontroller is currently one of the favorite tools of makers, and many teachers have used it in teaching or experiments. In addition, light-emitting diode (LED) smart lighting is the worldwide trend in lighting. There are many teaching demonstrations or applications of color addition using LEDs.[1–4] Furthermore, the Internet of Things (IoT) is a popular emerging technology today, and the sensor is the most important component in the perception layer of the IoT,[5] which makes teaching, research, or application related to sensors very important.[6–12] Therefore, this study shows that an Arduino microcontroller can be used as an experimental setup for the teaching of light color mixing, light intensity detection, and ambient temperature sensing via a tricolor (red, green, and blue [RGB]) LED and two types of sensors: photoresistors and thermistors. The setup has intuitive, concrete, and multifunctional features, and is expandable, which is different from the typical experimental setup designed for only a single specific purpose. It is also suitable for students learning about light color mixing and sensor-related physics course experiments or demonstrations, whether they be in high school or college.

Many instructors have presented several ways to teach students the physical knowledge related to light color mixing, light intensity detection, and ambient temperature sensing. Planinšič put R, G, and B LEDs together in a white Ping-Pong ball and used it as a color light mixer.[1] Millspaw et al. reported a light and color exploration kit including various LEDs, a mixing screen, absorption balls, and so on, allowing students to study additive and subtractive color mixing in a variety of ways.[2] Carvalho and Hahn used the Arduino Uno to set up a simple experiment to teach additive colors.[3] Nakadate et al. applied R, G, and B LEDs, cardboard, tracing paper, and mask patterns to develop a color mixer to teach about mixing colors.[4] Dias Tavares et al. used a calibrated photoresistor to verify the irradiance inverse square law and Malus's law.[6] Marinho et al. used a calibrated photoresistor for the measurements of reflected and transmitted light in optical experiments and verified the angular distribution of a Lambertian reflective material.[7] Setya et al. used a photoresistor and different color light sources placed at different distances to measure the resistance of the photoresistor and the light intensity with the aid of a multimeter and an Arduino-based lux meter, respectively. Their results indicate the relationship between the resistance of the photoresistor or the light intensity and distance or light color.[8] Nieddu presented electronic circuitry for high-accuracy and wide-range resistance measurements for thermistor sensor monitoring.[9] Boleman developed software to calculate an object's temperature from a user-supplied thermistor.[10] Gomes et al. reported an affordable simple talking calorimeter for the visually impaired based on an Arduino Uno and a thermistor.[11] Hendee et al. implemented a low-cost, high-precision sea temperature sensor that uses an Arduino microprocessor board and a high-accuracy thermistor.[12]

In the literature previously described, only the work of Refs. 3, 8, 11, and 12 are implemented through the Arduino platform, similar to the experimental setup in this study. But the biggest difference between the setup of this study and Ref. 3 is that students can instantly see the individual intensity percentage readings of the corresponding R, G, and B LEDs and the light mixing effect they make. In addition, compared to Ref. 8, this study explains in detail how to use a photoresistor to implement a lux meter, and then use it to measure the light intensity for physical experiments. This can help students improve their practical skills and understanding of physics. However, Ref. 8 only briefly mentions the hardware circuit and the application of a lux meter and completely omits the relevant details about the design and assembly of the meter. Moreover, Ref. 11 uses a Talkie library, a thermistor, and a Wheatstone bridge or a more complex voltage divider connected with an operational amplifier as a sensing circuit to develop a talking calorimeter for special education. The temperature value is mainly spoken aloud. To simplify the teaching procedure, however, this study only uses a thermistor and a voltage divider without an amplifier as the sensing circuit with still good accuracy, and the temperature value is mainly visually displayed. The use of the sea temperature sensor of Ref. 12 is similar to this study, but its temperature value is first recorded onto a memory chip, and finally, the temperature data is downloaded by specific software, which is completely different from this work. Ref. 12 focuses more on the practical application side rather than the actual teaching side. Furthermore, Refs. 3, 8, 11, and 12 are all designed for an experiment focusing on one topic of light color mixing, light intensity detection, or ambient temperature sensing. In contrast, this article describes a multipurpose integrated experimental platform that can simultaneously cover the above three exploration topics.

System setup

The appearance of the entire experimental setup demonstrated in this study is shown in Fig. 1. The system consists of a sensor circuit, mode switch, potentiometer, microcontroller unit (MCU) (Arduino Nano board), ULN2003A integrated circuit (IC), common anode RGB LED, two-digit common cathode seven-segment display, and USB 5-V power bank or other external 5-V power supply unit. Figure 2 shows the detailed circuit configuration of this setup. Through the use of

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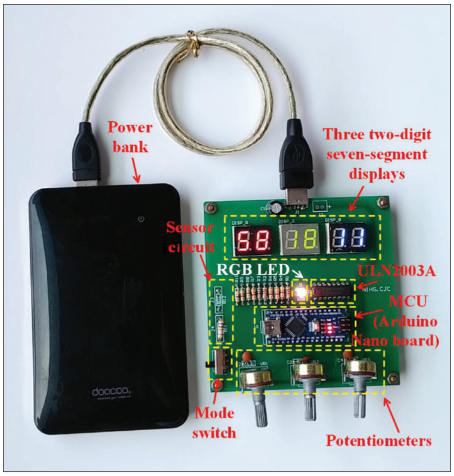

Fig. 1. The physical appearance of the experimental setup. The photoresistor or thermistor sensor is not yet installed in the sensor circuit. The corresponding sensor must be placed in the circuit when performing the light intensity detection or ambient temperature sensing experiment.

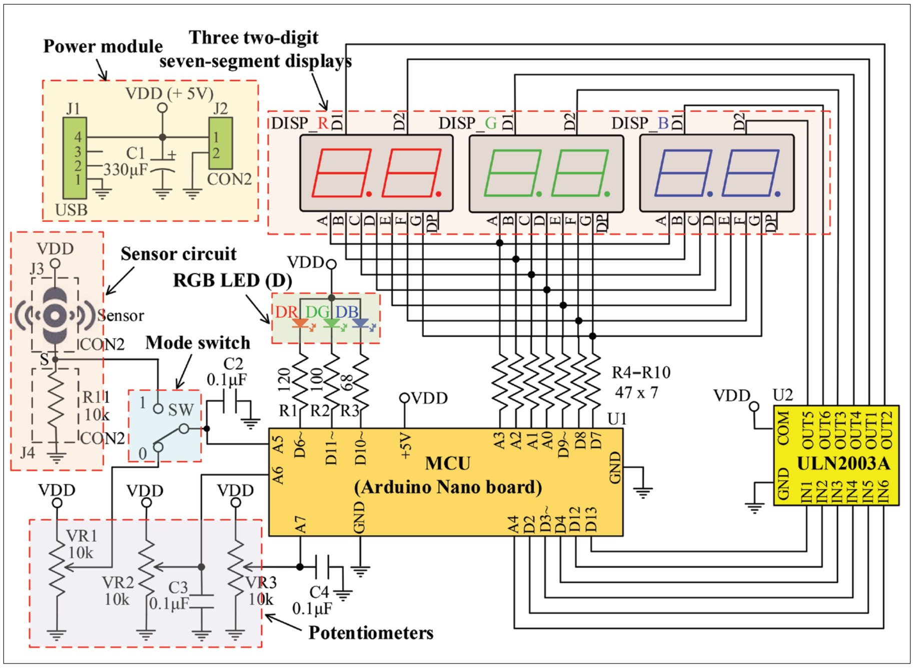

Fig. 2. Detailed circuit configuration of the experimental setup. CON2: 2 pin connector; DISP: display; SW: switch; USB: universal serial bus connector; VR: variable resistor.

RGB LED, photoresistor, and thermistor, the system has three operating modes: light color mixing, light intensity detection, and ambient temperature sensing. The MCU in Fig. 2 is coded with one of three different Arduino programs depending on the operation mode.[13–15] Considering space and portability, this system uses a smaller Arduino Nano board and is integrated on a square printed circuit board with a side length of 10.2 cm. However, using the circuit in Fig. 2, someone could also implement the same activity using an Arduino Uno (the most common Arduino), a breadboard, and the same other components.

The operating principles of the experimental system will be briefly explained in the following sections. Currently, the following sections are independent experiments. However, they can be further integrated into an intelligent lighting, display, and even energy-saving system that adjusts the color and/or brightness of RGB LEDs according to the environment's brightness and/or temperature.

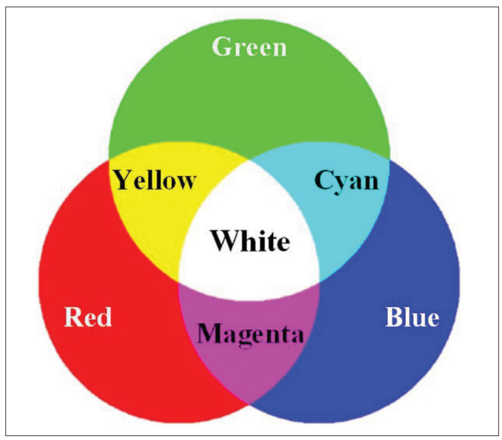

Fig. 3. Additive color mixing scheme.

Light color mixing

The trichromatic theory states that all colors in nature can be mixed from the three primary colors. As shown in Fig. 3, the addition and mixing of the three primary colors of red, green, and blue with different intensities can produce a variety of colors, which is called additive color mixing.

When the mode switch is set to 0, and the MCU is coded with the program in Ref. 13, this experimental setup is used to teach light color mixing using an RGB LED (Lucky Light, LL-U42RGBC2B-016). Voltages of 0–5 V are supplied to the analog input pins (A5–A7) of the MCU by adjusting the three 10-kΩ potentiometers (VR1–VR3), respectively. These voltages are converted to digital values of 0–1023 by the 10-bit analog-to-digital converter (ADC) in the MCU. These digital values are further mapped into the interval of 0–255. The digital signals of 0–255 then send pulse-width modulation voltage signals through the digital pins (D6, D11, and D10) of the MCU to adjust the individual light intensity of the red, green, and blue LEDs (DR, DG, and DB), and simultaneously change the resulting mixed light color of the RGB LED. In addition, the three previously mentioned digital signals from 0 to 255 are also converted to values from 0 to 100 concurrently, so that the three two-digit seven-segment displays (DISP_R, DISP_G, and DISP_B) can display the percentage values of light intensity (L_R, L_G, and L_B) of the DR, DG, and DB adjusted by VR1–VR3 (when the percentage value is 100, DISP_R, DISP_G, or DISP_B only displays 99). In the circuit, an ULN 2003A IC is used to drive three two-digit seven-segment displays. By adjusting VR1–VR3 so that the percentage values of the light intensity of DR, DG, and DB are individually $L_R = 58$, $L_G = 18$, and $L_B = 11$, the color mixing result of an RGB LED tends to be red, as shown in Fig. 1.

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During the light color mixing class, the teacher can ask students using VR1–VR3 to match the mixed light color of the RGB LED with several different colors provided by the teacher from the RGB Color Codes Chart.[16] The students will discover that there are millions of possible mixed light colors through the adjustment of VR1–VR3. The intuition and realization of this part of the experimental setup allow students to recognize immediately that the three RGB primary colors or the mixed colors of various light colors can be obtained by adjusting DR, DG, and DB with different intensity percentages. This setup can be further expanded to use three three-digit seven-segment displays to display values from 0 to 255, which directly corresponds to the true RGB values of the three RGB primary colors in the mixed color.

Light intensity detection

A photoresistor, also known as a light-dependent resistor (LDR), is a photosensitive device made of semiconductor materials such as cadmium sulfide (CdS) or cadmium selenide (CdSe). When the intensity of the incident light becomes stronger, the resistance of the photoresistor decreases due to the electron–hole pair generation.

The experimental setup in this study uses a CdS photoresistor (Waitrony, KE-10715) with diameter 5 mm for the teaching of light intensity detection. Figs. 4(a) and (b) show, respectively, the relative spectral response of the photoresistor and the relationship of the photoresistor resistance to the illumination under a light source with a color temperature of 2856 K.[17] If the mode switch is switched to 1, the MCU is coded with the program in Ref. 14, and the photoresistor resistance is assumed to be R_{LDR}, the analog voltage at the node S in the middle of the sensor circuit is

$$V_{\mathrm{S}} = \mathrm{VDD} \times R_{11}/(R_{11} + R_{\mathrm{LDR}}), \tag{1}$$

where VDD is the power supply voltage (5 V). When V_{S} is read by the analog pin A5 of the MCU, the digital value of V_{S} after the 10-bit ADC conversion is given by

$$V_{\mathrm{S\_ADC}} = 1023 \times R_{11}/(R_{11} + R_{\mathrm{LDR}}). \tag{2}$$

Through proportional conversion, we obtain

$$V_{\mathrm{S\_ADC}}' = V_{\mathrm{S\_ADC}} \times (100/1023) = 100 \times R_{11}/(R_{11} + R_{\mathrm{LDR}}), \tag{3}$$

and the digital value of $V_{\mathrm{S\_ADC}}'$ is displayed on DISP_R using the same circuit mentioned earlier. As

$$R_{\mathrm{LDR}} = R_{11} \times (100/V_{\mathrm{S\_ADC}}' - 1), \tag{4}$$

where $R_{11} = 10\ \mathrm{k}\Omega$, R_{LDR} can be derived from the digital value of $V_{\mathrm{S\_ADC}}'$. The light intensity of the photoresistor can then be estimated according to Fig. 4(b). To avoid the variation of the displayed value on DISP_R, the digital value of $V_{\mathrm{S\_ADC}}'$ before being displayed is averaged 200 times in the MCU program. Taking the value 47 in Fig. 4(c) as an example, we can derive that $R_{\mathrm{LDR}} = 11.3\ \mathrm{k}\Omega$, which corresponds to the equivalent illumination intensity of about 10 lux for a light source with a color temperature of 2856 K. The experiment in this paper is limited by the data shown in Fig. 4(b), so the effective range of light intensity detection is between 1 and 1000 lux.

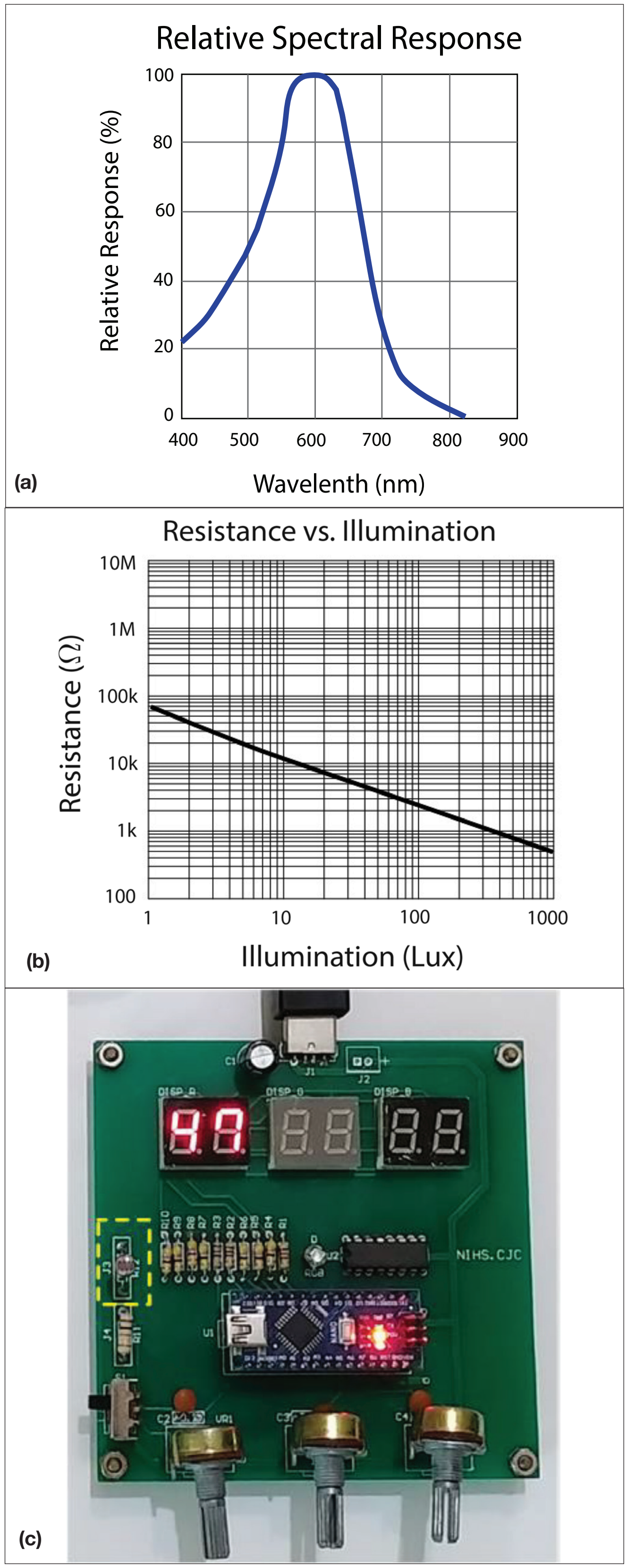

Fig. 4. (a) The relative spectral response of the photoresistor used in the experiment. (b) The relationship between resistance and illumination for the photoresistor.[17] (c) Result of the light intensity detection experiment. The yellow rectangle shows the photoresistor, and the detection intensity value is 47. The mode switch is set to 1.

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In the teaching of light intensity detection, the teacher can first guide the students to understand the difference between the three common optical units of lux, lumen, and watt, and let the students use this part of the experimental setup to deduce the dark resistance of the photoresistor from the V_{S_ADC}' value in a dark room. Next, detect the light intensity under several light sources or lighting conditions such as a 60-W bulb at 1 m, a 1-W miniature Edison screw bulb at 10 cm, fluorescent lighting, and a well-lighted room. Then take a 12-V bulb (night lamp) as the light source, change the vertical distance between the light source and the photoresistor surface (e.g., to 5–60 cm), measure and record the light intensity value, and, finally, draw a graph to verify the light intensity is inversely proportional to the distance squared. In addition, this experimental setup can use different photoresistors with various specifications to increase the detection range of light intensity.

Ambient temperature sensing

A thermistor (TSR) is a variable resistor made of ceramic or polymer semiconductor materials. For a negative temperature coefficient (NTC) thermistor, its resistance decreases as the temperature increases. The temperature–resistance curve of the NTC thermistor can be represented as the B parameter equation derived from the Steinhart–Hart equation[18]:

$$\frac{1}{T}=\frac{1}{T_0}+\frac{1}{B}\ln\left(\frac{R}{R_0}\right), \tag{5}$$

where T is the absolute temperature in kelvins, R is the resistance in ohms, and R_0 is the resistance of the thermistor measured at temperature T_0. B is a constant coefficient expressed in kelvins, which depends on the material characteristics of the thermistor.

The NTC thermistor (Amphenol, NK103C1*5) used in this study for teaching ambient temperature sensing has a B parameter (25/85 °C) of 3977 K ± 0.75%, T_0 = 25 °C (298.15 K), and R_0 = 10 kΩ ± 5%. If the mode is switched to 1, the MCU is coded with the program in Ref. 15, and the sensor is changed to a thermistor assumed to have a resistance of R_{TSR}, the converted digital value of the analog voltage read from the analog pin A5 of the MCU is also

$$V_{S\_ADC} = 1023 \times R_{11}/(R_{11} + R_{TSR}), \tag{6}$$

which means that

$$R_{TSR} = R_{11} \times (1023/V_{S\_ADC} - 1). \tag{7}$$

The absolute temperature T (in kelvins) can be converted after substitution of the R_{TSR} into Eq. (5), and this resulting value is subtracted from 273.15 to obtain the Celsius temperature. Using the same display circuit as in the light color mixing, we let DISP_R display the temperature value but DISP_G display a fixed unit symbol C for Celsius temperature. Figure 5 shows the display when the ambient temperature sensed by the thermistor is 28 °C.

When teaching ambient temperature sensing, the teacher can ask the students to hold the thermistor between their thumbs and forefingers to observe whether the temperature

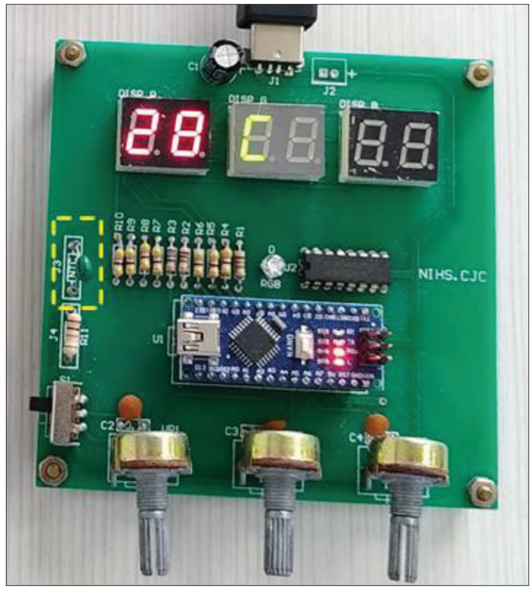

Fig. 5. Result of ambient temperature sensing experiment. The yellow rectangle shows the thermistor, and the sensing temperature is 28 °C. The mode switch is set to 1.

reading increases, and see how close it can get to 37 °C (body temperature). In addition, a heated soldering iron can be placed next to the experimental setup to increase the ambient temperature. Meanwhile, a mercury thermometer can be used to verify the accuracy of the setup in the measurement of the ambient temperature. Finally, try to let students practice estimating the possible experimental errors in the following two situations: 1) Known voltage is read into the MCU by the 10-bit ADC, and the error of fixed resistor R_{11} is ±5%; please calculate the expected error in the estimation of R_{TSR}. 2) If the thermistor error is ±5% and all other processes are accurate, what is the estimated error in the temperature measurement? This part of the experimental setup can be expanded to display the temperature to the next decimal place. It can also be modified to use DISP_R, DISP_G, and DISP_B to display positive and negative temperatures. Furthermore, if a stainless-steel waterproof thermistor is used, it can detect liquid or soil temperature as well. Thus, this setup can be widely used in conjunction with various physical experiments related to temperature measurement.[10,19,20]

Conclusions

In this study, an Arduino microcontroller is used to demonstrate a multifunctional experimental setup suitable for the teaching of light color mixing, light intensity detection, and ambient temperature sensing. It has the characteristics of intuition and concreteness, and the related physical values can be directly displayed on the seven-segment displays, which helps to deepen the students' learning. It is also small, lightweight, and easy to carry. It can be operated in ordinary classrooms and saves time for teachers to prepare experimental teaching materials. This setup can be expanded to include various application topics such as color mixing, color change, and intensity control of RGB LEDs. Different sensors such as sound sensors, humidity sensors, airflow sen-

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sors, pressure sensors, and so on can also be used to carry out extended experiments. In addition, this experimental setup has been tried out in high school physics courses for three years, and the feedback from students is very positive.

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