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A Microcontroller-Based Experiment to Determine the Magnetic Field Near a Straight Current-Carrying Wire

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It is well known that the needle of a compass in a magnetic field deflects, and that a compass near a conductive wire carrying a stable electric current deflects its needle. The only explanation of this observation is that the current-carrying wire creates a magnetic field around it. The strength of the magnetic field at any point near the wire depends on the strength of the current and the distance from the wire. Analysis of the magnetic field created by a long straight current-carrying wire has an important place in magnetism teaching. Therefore, the aim of this study was to develop a low-cost experimental setup to collect real-time data for the analysis of the magnetic field near a long straight wire.

Ampère's law, defined by Eq. (1), is useful in calculating the magnetic field created by current distributions having high degree of symmetry[1, 2]:

$$\oint \boldsymbol{B} \cdot d\boldsymbol{s} = \mu_0 I. \qquad (1)$$

In this equation, $\boldsymbol{B}$ is the magnetic field, $d\boldsymbol{s}$ is a small length element, I is the total steady current passing through the surface bounded by the closed path, and μ_0 is the permeability of free space. Ampère's law can be used to determine the magnetic field around a long straight wire carrying steady current, as shown in Fig. 1.

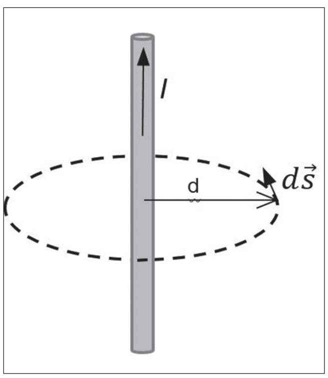

Fig. 1. Current-carrying long straight wire.

According to the right-hand rule, the magnetic field lines around the wire are in the form of circles and extend in planes perpendicular to the wire. Due to symmetry, $\boldsymbol{B}$ at each point of this circle is parallel to $d\boldsymbol{s}$ and its magnitude is fixed. So

$$\oint \boldsymbol{B} \cdot d\boldsymbol{s} = \oint B \cdot ds = B\oint ds = B(2\pi d) = \mu_0 I, \qquad (2)$$

and B can be calculated as

$$B = K\frac{I}{d} \quad (\text{where } K = \frac{\mu_0}{2\pi}). \qquad (3)$$

In the literature, there are studies that aim to measure the magnetic field using a low-cost experimental setup.[3-8] Maheswaranathan[3] used a narrow and long rectangular multi-loop experimental design to define the magnetic field of a straight wire, and measured the magnetic field at the center of the rectangular loop for different current values. Ogawara, Bhari, and Mahrley[4] used a smartphone magnetic field sensor in their experimental setup to determine the magnetic field formed by a circular electric current. In many studies[5-8] using a sensor to determine the magnetic field of coils or solenoids, the sensor data were processed with the Arduino. The studies mentioned above are mostly concerned with measuring the magnetic field of a circular wire, a coil, or a solenoid. According to Maheswaranathan,[3] to verify Ampère's law, in introductory physics laboratories solenoids and toroids are often preferred to a long conductive wire carrying constant current, whose very small magnetic field even at large currents is difficult to measure. Nevertheless, the analysis of the magnetic field of a long straight current-carrying wire is extremely important as it is a fundamental application of Ampère's law. Therefore, in this study, we aimed to develop a low-cost experimental setup that allows analyzing the dependence of the magnetic field on current and distance.

Method

In this study, experimental data were collected using distance, current, and magnetic field sensors. All sensors are sensitive and cost effective. For the processing of data collected through sensors, the Arduino Uno was selected as an easily accessible and low-cost microcontroller. The combined cost of all electronic components in the experimental setup (including Arduino) was approximately \$50. The connections of the sensors are shown in the circuit diagram in Fig. 2. The sensors' V_{CC} and GND pins are, respectively, connected to the Arduino's 5V and GND pins to activate the magnetic sensor, current sensor, and distance sensor. In order to collect the data from the sensors, the current sensor's VO pin of the current sensor is connected to the A0 pin, the distance sensor's V_{OUT} pin is connected to the A1 pin, and the magnetic sensor's communication pins (SCL and SDA) are connected to the Arduino's A4 and A5 pins. PLX-DAQ macro was used to transform the Arduino data into real-time graphics. PLX-DAQ is a Parallax microcontroller data acquisition add-on tool for Microsoft Excel.[9] This macro enables a real-time communication between Microsoft Excel and any microcontroller that supports serial port protocol.

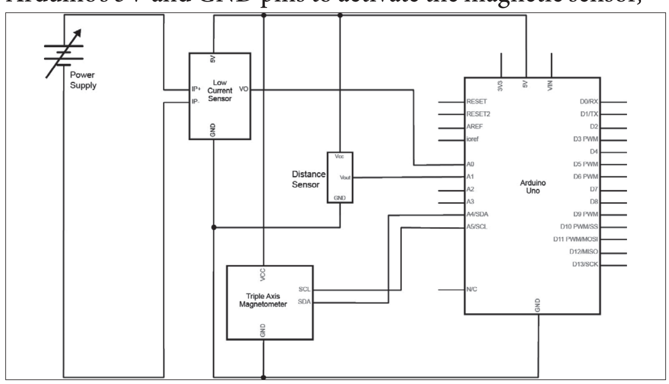

Fig. 2. Circuit diagram.

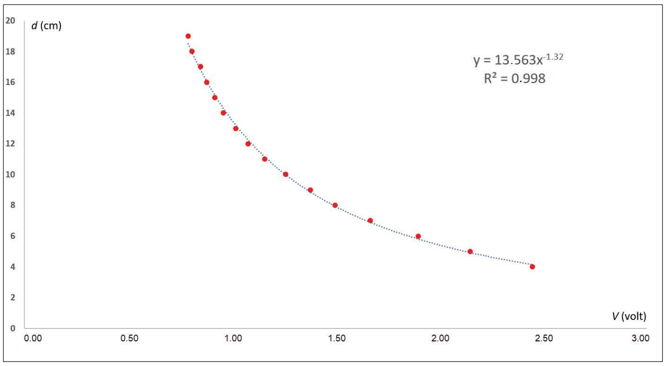

Fig. 3. Distance–voltage graph for distance sensor.

Measurement of distance

The GP2Y0A41SK0F Sharp analog distance sensor[10] was used to determine the distance between the wire and the magnetic field sensor. GP2Y0A41SK0F is a distance sensor consisting of a combination of a PSD (position sensitive detector), an IR-LED (infrared light-emitting diode), and a signal processing circuit. This sensor can make sensitive and accurate length measurements from 4 cm to 30 cm. This device outputs the voltage corresponding to the detection distance. Therefore, to obtain quantitative distance values, it is necessary to convert the voltage data to length data. This was achieved by placing a reflective surface at a certain distance from the sensor, and measuring the voltage value obtained from the sensor and the length value read from the ruler. This measurement was repeated for 16 different distance values and a voltage–distance graph was drawn in Excel (Fig. 3). Finally, the following equation, which gives the distance d in centimeters when the voltage V is input in volts, was reached:

$$d = 13.563V^{-1.32} \text{ cm}. \tag{4}$$

Placing Eq. (4) in the code index[11] allowed the conversion of voltage values measured with the Arduino's analog pins into distance values.

Measurement of magnetic field

The Honeywell QMC5883L, a surface-mount, multi-chip, and three-axis magnetic sensor,[12] was used to determine the magnetic field. It is low cost and allows low field measurements. Due to its small size, it is placed on a wooden block (4×4 cm), allowing easier detection by the distance sensor. Thus, it is provided to be detected more easily by the distance sensor.

Measurement of current

The ACS712 current sensor was used to determine the current passing through the wire. The ACS712 is a Hall effect-based linear current sensor.[13] In the experiment, the sensor was connected in series between the wire and the power source.

Experimental setup

The experimental setup consists of a power supply, a magnetic sensor, a distance sensor, a current sensor, a microcontroller, and a 2-m-long copper wire (Fig. 4). The magnetic sensor is placed on a wooden block so that the motion sensor can easily and accurately determine its position. This also ensures that the middle point of the magnetic sensor and the wire are at the same height throughout the experiment. The front face of the wooden block is covered with white paper to facilitate reflection. The distance sensor is able to collect reliable data in the range of 4 to 30 cm. For this reason, the distance sensor was fixed at 6 cm away from the wire in order to ensure accurate measurement of the distance, even when the magnetic sensor is very close to the wire.

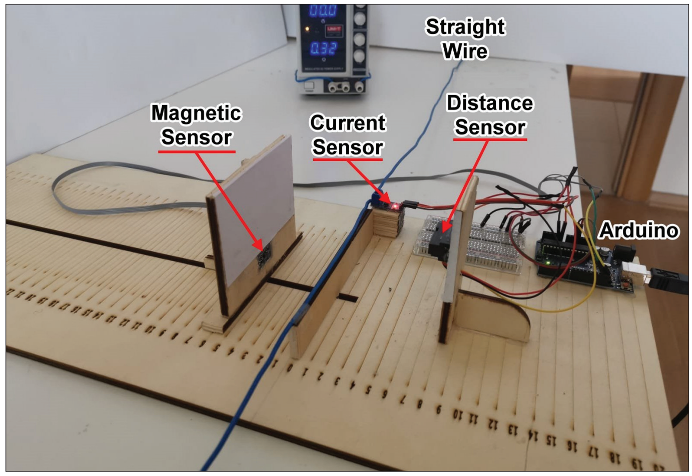

Fig. 4. Experimental setup.

Experimental procedure

PLX-DAQ must be run before starting the experiment, and the suitable port and bound rate must be selected in the window that opens.

Determining the relationship between current and magnetic field

The first stage of the experiment is to determine the relationship between current and magnetic field. For this purpose, the magnetic sensor is fixed at a certain distance from the wire, and it remains in position throughout the experiment. Even though in the initial stages no current flows through the wire, the sensor will show a reading due to the external magnetic field. Therefore, before the experiment, it is necessary to carry out the reset process by pressing the button on the Arduino. After this, the sensor will only read the magnetic field generated by the wire. Next, the current is gradually increased from 0 to 5 A, and the data are recorded in five columns as seen in Fig. 5.

The first column contains the values read by the distance sensor, the second column the values read by the current sensor, and the third the values read by the magnetic sensor. In this part of the experiment, the graph of the magnetic field strength, which depends on the current intensity, is drawn in real time using the second and third column data. The fourth and fifth columns contain the K and μ_0 constants, calculated using the first three variables. Figure 6 shows the real-time magnetic field–current graph reached during the experiment.

The average of the μ_0 values determined at the end of the

Distance (m)	Current (A)	Magnetic Field (T)	K(T·m/A)	μ0(T·m/A)
0.021	0.21	1.97E-06	1.95E-07	1.22E-06
0.021	0.21	2E-06	1.95E-07	1.22E-06
0.021	0.29	2.74E-06	1.97E-07	1.24E-06
0.021	0.45	4.36E-06	2.02E-07	1.27E-06
0.02	0.72	7.13E-06	2.01E-07	1.26E-06
0.021	0.82	8.1E-06	2.03E-07	1.28E-06
0.021	0.91	8.95E-06	2.03E-07	1.27E-06
0.021	0.99	9.84E-06	2.04E-07	1.28E-06
0.021	1.08	1.07E-05	2.04E-07	1.28E-06
0.02	1.16	1.15E-05	2.03E-07	1.28E-06
0.021	1.24	1.23E-05	2.08E-07	1.31E-06
0.02	1.39	1.4E-05	2.05E-07	1.29E-06
0.02	1.48	1.47E-05	2.04E-07	1.28E-06
0.021	1.54	1.53E-05	2.07E-07	1.3E-06
0.02	1.6	1.6E-05	2.03E-07	1.28E-06
0.02	1.71	1.7E-05	2.02E-07	1.27E-06
0.021	1.87	1.87E-05	2.08E-07	1.3E-06
0.021	1.99	2E-05	2.07E-07	1.3E-06
0.02	2.07	2.07E-05	2.05E-07	1.29E-06
0.021	2.2	2.2E-05	2.07E-07	1.3E-06
0.021	2.35	2.34E-05	2.07E-07	1.3E-06
0.021	2.44	2.44E-05	2.08E-07	1.31E-06
0.02	2.55	2.56E-05	2.05E-07	1.29E-06
0.021	2.79	2.79E-05	2.06E-07	1.3E-06
0.021	2.87	2.88E-05	2.08E-07	1.3E-06
0.02	2.96	2.96E-05	2.04E-07	1.28E-06
0.021	3.15	3.16E-05	2.12E-07	1.33E-06
0.02	3.28	3.3E-05	2.05E-07	1.29E-06
0.021	3.53	3.55E-05	2.08E-07	1.31E-06
0.021	3.6	3.62E-05	2.08E-07	1.31E-06
0.02	3.65	3.67E-05	2.05E-07	1.29E-06
0.021	3.7	3.72E-05	2.08E-07	1.31E-06
0.021	3.74	3.75E-05	2.1E-07	1.32E-06

Fig. 5. View of the spreadsheet after the data were transferred.

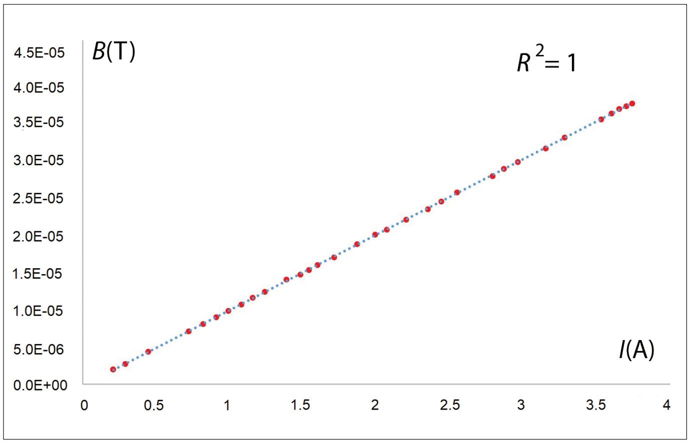

Fig. 6. The magnetic field strength–current graph at constant distance.

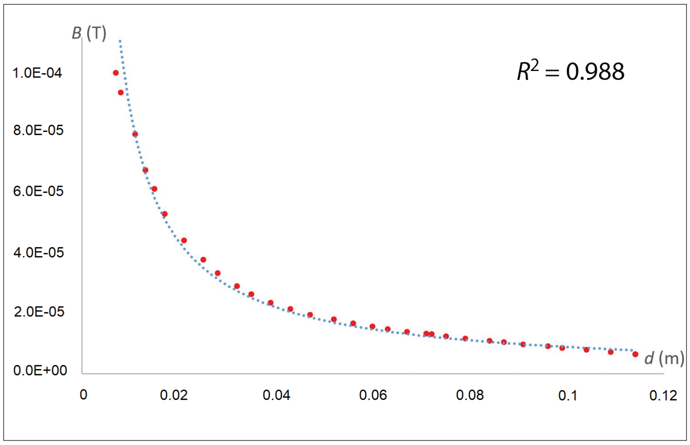

Fig. 7. Magnetic field strength–distance graph at constant current.

first stage of the experiment was calculated as 1.29×10^{-6} (T · m/A). The constant d value was measured by the distance sensor in the range of 0.020 to 0.021 m. The absolute uncertainty in the measurement of the distance was calculated as 0.0005 m and the percentage uncertainty was calculated as 2.4%. The best value of the B–I graph's slope and its uncertainty were estimated as 1.01×10^{-5} (T/A) and 0.09×10^{-7} (T/A), respectively, by using the LINEST function in Excel, and the percentage uncertainty was calculated as 0.09%. Using these data, the total percentage uncertainty in determining the average of the μ_0 was calculated as about 2.5%. From these values one obtains $\bar{\mu}_0 = (1.29 \times 10^{-6} \pm 2.5\%)$ T · m/A.

Determining the relationship between distance and magnetic field

At this stage of the experiment, the magnetic sensor's distance from the wire is changed, while keeping the current through the wire constant. As in the first stage of the experiment, when the current passing through the wire is zero, pressing the button on the Arduino performs the reset process. The magnetic sensor is placed at a maximum distance of 30 cm from the distance sensor, and the current is fixed to a certain value. As the current flows through the wire, the magnetic sensor will begin to read the magnetic field at its location. Simultaneously the distance sensor will detect the location of the magnetic sensor and determine its distance to the wire, thus determining the distance of a certain point to the wire and the magnetic field strength at that point. The data collection continues as the magnetic sensor is moved towards the wire. Figure 7 shows the graph of the magnetic field strength according to distance in the range of 0 to 10 cm at 4-A constant current. Due to the high current, students should be warned against touching uninsulated connection points of the circuit. The data collection part of the experiment can be viewed in the video[14] recorded by the authors.

Conclusion

This research involved the design of a low-cost experiment to determine the magnetic field near a straight current-carrying wire. In the experiment it was possible to observe the change of magnetic field strength depending on both distance and current intensity in real time. This makes the experiment an effective activity both in the laboratory and in the classroom. In the experiment, the effect of the external magnetic field can be reset by pressing a single button, enabling students to access results without making additional calculations. Magnetic permeability of free space was calculated as 1.29×10^{-6} (T· m/A) with the data collected using the experimental setup. This value is about 2.38% higher than the value of 1.26×10^{-6} (T· m/A), which is known as the magnetic permeability of free space.

This experimental setup can be used as an effective learning activity through the investigation of the magnetic field created by a current-carrying conductive wire. Rather than being directly provided with the formula, the students have to interpret the graphs drawn in real time, identify the relationships between magnetic field, current, and distance, and create a mathematical model. For example, using the first graph, students can easily establish the linear relationship ($B \propto I$) between the current and magnetic field strength, and, using the second graph, establish the inversely proportional relationship ($B \propto 1/d$) between the distance and the magnetic field strength. Thus, using this information, students arrive at the equation $B = (\text{constant})I/d$.

The most important limitation of this experiment concerns distance measurement. The distance sensor can only take reliable measurements in the range of 4 to 30 cm. The distance sensor was placed 6 cm behind the wire, in order to measure at distances less than 4 cm from the wire. If the magnetic sensor is placed 1 cm from the wire, this point will actually be 7 cm for the distance sensor. Considering this situation, 6 cm was subtracted from the value read by the distance sensor to determine the distance from the wire in the code index. Thus, for short distances, the magnetic sensor was kept within the detection limits of the motion sensor.

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