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Magnetic Field on A Square Helmholtz Coil Experiments Using Remote Laboratory

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ABSTRACT

This research aims to explore the potential for innovation in physics teaching methods by utilizing remote laboratory technology for square Helmholtz coil magnetic field experiments. This research uses experiments with two variations of the distance between coils, accessed through an online portal-based remote laboratory, and magnetic field data taken using a Vernier magnetic field sensor. The results showed that the remote experiment produced data similar to the analytical predictions, with relative errors of 7.45% and 6.06% for the two different inter-coil distances. In conclusion, remote laboratories have great potential to support innovation in physics teaching methods. This research implies that remote experiments can be an efficient and accurate tool in online physics learning, providing a helpful practicum experience despite being conducted remotely.

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I. Introduction

Physics experiments, particularly those related to magnetic fields, play a vital role in teaching fundamental physics concepts, such as magnetic force, Biot-Savart law, and Ampère's law [1], [2]. Magnetic field experiments use devices such as Helmholtz coils to create and manipulate magnetic fields that can be measured and analyzed [3]. However, such experiments often face significant technical and logistical challenges, especially in their setup in traditional physics laboratories. Some of these challenges include space limitations, the high cost of equipment, and difficulties in providing equal access to all students, especially those in remote locations [4]. In many educational institutions, limited equipment and budgets hinder the ability to conduct hands-on experiments, affecting students' understanding of physics concepts.

Along with the advancement of digital technology and the internet, a new learning innovation called remote laboratory has emerged [5]-[7]. Remote laboratories allow students to access and run physics experiments through devices that can be controlled remotely [5]. The basic concept behind remote laboratories is creating a learning experience equivalent to traditional physics experiments but without limitations in space or physical location. Users can access experimental devices and tools online, control instruments directly, and obtain experimental data that can be processed and analyzed in real-time [4]. The existence of this technology overcomes the barriers that exist in physics education, especially those related to limited accessibility and cost.

Remote laboratories for magnetic field experiments represent a significant advance in educational methodology, particularly in physics and engineering. By integrating technology, remote laboratories facilitate the exploration of magnetic phenomena through remote access to a real experimental setup. This approach not only increases accessibility but also promotes a deeper understanding of the complex concepts associated with magnetic fields. On the other hand, this approach still has limitations in accuracy and interactivity that must be continuously evaluated to be applied more widely and effectively in various educational institutions.

One of the main advantages of remote laboratories is their ability to provide real-time data acquisition and visualization of magnetic fields. For example, Ishafit et al. [3] developed an Arduino and LabVIEW-based remote data acquisition system specifically for experiments involving magnetic fields generated by coils. The system supports experimental physics learning by allowing students to interact remotely with the material. Similarly, Bjekić et al. [8] demonstrated the effectiveness of remote experiments in teaching about rotating magnetic fields in AC machines, highlighting that such a setup can improve student outcomes and the quality of education in electrical engineering. However, the limited application of remote laboratories in magnetic field experiments, especially using square Helmholtz coils, is a gap that needs further research.

The urgency of this research is very relevant considering the great potential that remote laboratories have in supporting the teaching of magnetic field experiments more effectively and widely. This research aims to fill the gap by exploring and analyzing the potential use of remote laboratories in Square Helmholtz Coil magnetic field experiments. This research will evaluate the quality of the tools and systems used in the Square Helmholtz Coil experiment. Therefore, this research aims to explore the potential for innovation in physics teaching methods by utilizing remote laboratory technology and comparing the results of experiments conducted using remote laboratories with analytical methods.

This research contributes to developing a new methodology in applying remote laboratories that are more specific to magnetic field experiments, especially square shapes. This research is expected to provide new insights into the application of technology in physics education and suggest further development in the design of remote laboratory systems for square magnetic field experiments. Thus, this research contributes in theory and provides practical guidance for physics educators and educational technology developers.

II. Theory

Square Helmholtz coil

The square Helmholtz coil is a modification of the classic design by replacing the circular coil with a square coil [9]-[11]. This configuration produces a uniform magnetic field over a given volume between the coils. The square Helmholtz coil configuration consists of two identical symmetrical coils with a distance between coils and a coil side length, *l* [12].

The two coils are electrified with the same magnitude so that a magnetic field will arise around the coil [13]. The magnitude of the magnetic field produced by this coil is believed to depend on the permeability of the magnet, the number of turns, the strength of the current flowing in the two coils, the length of the coil, and the distance between the two coils [14].

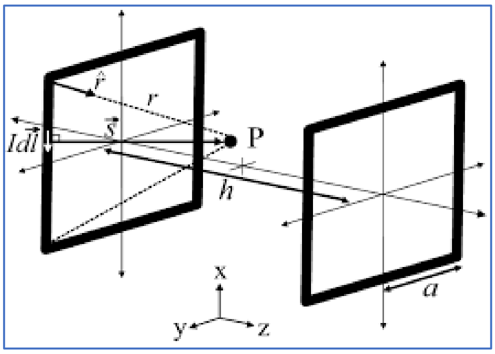


Figure 1. Schematic diagram of the Helmholtz configuration

In Figure 1, it is shown that the coils are parallel to the distance between the coils *h*, and if the same current powers both coils, it will produce a magnetic field at point *P* according to equation (1) [12].

Remote Experiment

Remote experimentation is an experimental method that allows users to conduct experiments remotely via internet access [15], [16]. This system integrates experimental hardware with digital communication technology so that users can control experiments in real time without being at the laboratory site [17].

The main advantages of remote experimentation are its accessibility and flexibility. With this technology, users from different locations can perform the same experiment without the need to be physically present. In addition, remote experiments support collaborative learning [18]. This technology also reduces laboratory operational costs, allowing multiple users to share hardware.

$$\vec{B}(z) = \frac{2\mu_0 N I a^2}{\pi}\left[\frac{1}{\left(a^2+\left(z+\frac{h}{2}\right)^2\right)\left(2a^2+\left(z+\frac{h}{2}\right)^2\right)^{1/2}}+\frac{1}{\left(a^2+\left(z-\frac{h}{2}\right)^2\right)\left(2a^2+\left(z-\frac{h}{2}\right)^2\right)^{1/2}}\right] \tag{1}$$

III. Method

Square Helmholtz coils

A square Helmholtz coil is made by winding a 0.05 cm diameter wire on a 0.03 cm thick cover printed using a 3D printer. In this study, the coil was made with 100 turns, dimensions 9×9 cm. Figure 2 shows a square view of the Helmholtz coil. Two identical coils are then arranged at a certain distance, as in Figure 1, and then electrified to produce a magnetic field.

(a). Front view (b). Side view

Figure 2. Square Helmholtz coils

Experimental setup

This research is included in the experimental research. The Helmholtz coil is electrified with an electric current of $I = 0.39$ amperes. The data obtained is the magnetic field at each point around the coil, ranging from $z = -10$ cm to $z = 10$ cm, with the starting point ($z = 0$) in the middle of the two coils. A negative sign indicates that the point is to the left of the centre point. Magnetic field data was sampled using a Vernier Magnetic Field Sensor ranging from 0.32 to 6.4 mT. Figure 3 shows the experimental apparatus used.

The apparatus used in this study was accessed online based on a remote laboratory through the portal http://rphylab.pf.uad.ac.id/sistem by requesting a username and password to the administrator via email rphylab@gmail.com. Using the live streaming video feature, users observe the experimental device, control equipment, and data acquisition process [19].

Data Analysis

In this experiment, there are two variations of the distance between coils. First, the coil spacing is half of the coil side length ($h = 0.5l = a$), so equation (1) can be written as equation (2). While the second distance between coils is changed to 2 times, so equation 2 can be written into equation (3).

IV. Results and Discussion

The results of the magnetic field experiment on a square Helmholtz coil from a distance can be seen in Figure 4 via the website. The experiment involves setting the sensor distance, measured from the centre point of the Helmholtz coil, ranging from -10 cm to 10 cm at 1 cm intervals. The user can control the experiment through the Graphical User Interface (GUI) on the computer screen. This GUI facilitates interaction between the user, the software, and the hardware, enabling remote experiment control with immediate feedback and programmable logic controller settings [20]-[23]. In addition, users can monitor the movement of the magnetic field sensor while data is being collected and communicate with the administrator via video teleconferencing.

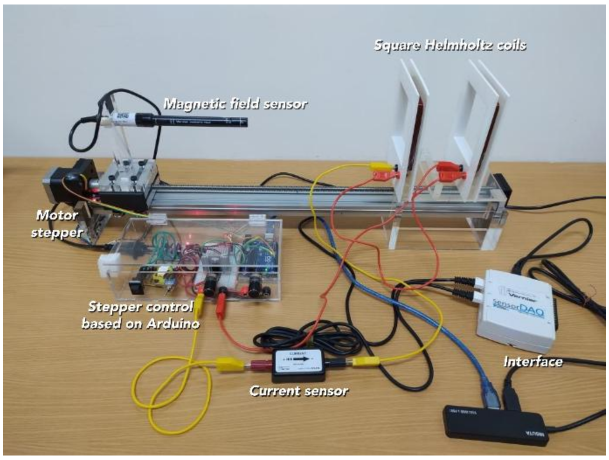
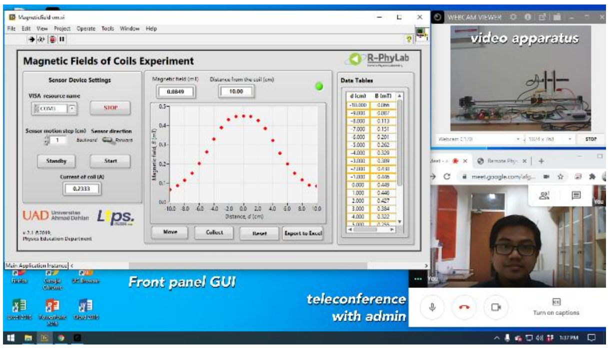


Figure 3. Apparatus magnetic field experiments using a square Helmholtz coil



VISA resource name: COM3

Sensor motion step (cm): 1

Current of coil (A): 0.2333

Magnetic field (mT): 0.0849

Distance from the coil (cm): 10.00

d (cm)	B (mT)
-10.000	[illegible]
-9.000	0.087
-8.000	0.113
-7.000	0.151
-6.000	0.201
-5.000	0.262
-4.000	0.329
-3.000	0.389
[illegible]	[illegible]
-1.000	[illegible]
0.000	0.449
1.000	0.446
2.000	0.427
3.000	0.384
4.000	0.322

Figure 4. Experiment results and GUI display that can be accessed remotely

$$\vec{B}(z)=\frac{2\mu_0 NIa^2}{\pi}\left[\frac{1}{\left(\left(a^2+\left(z+\frac{a}{2}\right)^2\right)\left(2a^2+\left(z+\frac{a}{2}\right)^2\right)\right)^{1/2}}+\frac{1}{\left(\left(a^2+\left(z-\frac{a}{2}\right)^2\right)\left(2a^2+\left(z-\frac{a}{2}\right)^2\right)\right)^{1/2}}\right] \tag{2}$$

$$\vec{B}(z)=\frac{2\mu_0 NIa^2}{\pi}\left[\frac{1}{\left(\left(a^2+\left(z+\frac{2a}{2}\right)^2\right)\left(2a^2+\left(z+\frac{2a}{2}\right)^2\right)\right)^{1/2}}+\frac{1}{\left(\left(a^2+\left(z-\frac{2a}{2}\right)^2\right)\left(2a^2+\left(z-\frac{2a}{2}\right)^2\right)\right)^{1/2}}\right] \tag{3}$$

The experimental results of magnetic field distribution around the Helmholtz coil with the distance between the half of the side length coils, $a = (4.5 \pm 0.5)$ cm, are shown in Figure 5.

Based on Figure 5, the experimental data is coded with a "Cross," while the analytical results obtained from equation (2) are coded with a "Redline." In comparing the two approaches, it can be seen that although there are significant similarities in the data patterns, there are measurable differences. By comparing the experimental data with the analytical calculation results, a relative error of 7.45% was obtained, indicating a slight discrepancy between the experimental results and the analytical model. However, this relatively small relative error indicates that the analytical model is quite reliable in describing the phenomena that occurred in the experiment, and the error is still within acceptable tolerance limits for experiment-based learning purposes.

Meanwhile, the experimental results when the distance between the coils is equal to the side length, $2a = (9.00 \pm 0.50)$ cm, are shown in Figure 6. The experimental data are coded with the symbol "Cross," while the analytical results calculated based on equation (3) are coded with the symbol "Redline." In comparing these two approaches, there is a significant similarity in the data patterns, although there are measurable differences. By comparing the experimental data with the analytical calculation results, a relative error of 6.06% was obtained, indicating a slight difference between the experimental results and the analytical model.

Both of these show that the experimental results of the magnetic field around a square Helmholtz coil accessed online remotely agree with the predicted results of the analytical approach using the Biot-Savart Law. Although very small, the error obtained in this experiment is because the magnetic field permeability values used in the analytical approach based on equations (2) and equation (3) are the permeability of the magnet in a vacuum, μ_0. Meanwhile, the equipment used was not placed in a vacuum. This result can be corrected by placing the equipment in a space with the magnetic permeability of a vacuum. In addition, it can also be done by making corrections to the magnetic permeability values used in the analytical approach using equations (2) and (3).

Despite the shortcomings, the experimental results show a high level of accuracy. Thus, the magnetic field experiment on a square Helmholtz coil using a remote laboratory can be used to support the physics learning process through online experiments.

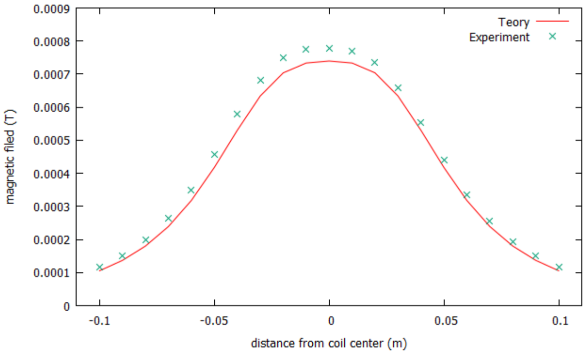


Figure 5. Distribution of the magnetic field around the coils for the distance between the coil a

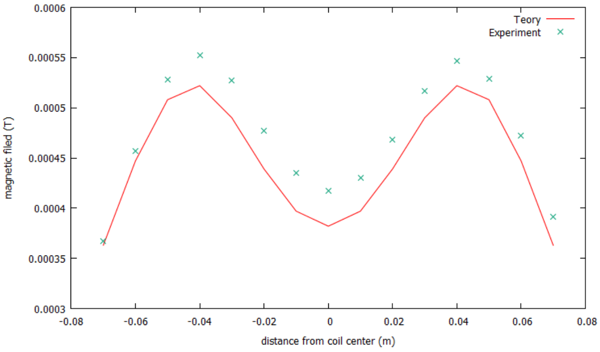


Figure 6. Distribution of the magnetic field around the coils for the distance between the coils $2a$

V. Conclusion

This study shows that using remote laboratories for magnetic field experiments on square Helmholtz coils has significant potential to support innovation in physics teaching methods. The remotely conducted experimental results show a reasonably high similarity with analytical predictions based on Biot-Savart Law, with a measured relative error of 7.45% at coil spacing $a = (4.5 \pm 0.5)$ cm and 6.06% at coil spacing $2a = (9.00 \pm 0.50)$ cm. Although there is a slight discrepancy between the experimental data and the analytical model, the error is still within acceptable tolerance limits, indicating that the experimental data is reliable. This slight discrepancy can be explained by the difference in magnetic permeability between the experimental chamber and the vacuum, which can be improved by correcting the magnetic permeability values in the analytical calculation. Thus, this experiment can be used as an online physics learning tool, providing an efficient and accurate practicum experience even when conducted remotely.

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Declarations

Author contribution	**:**	Ishafit was responsible for the entire research project. He collaborated with Moh. Irma Sukarelawan in writing and revising the manuscript. Diah Ayu Kustianingsih was responsible for developing the experimental apparatus. Toni Kus Indratno was responsible for data analysis and interpretation.
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Additional information	**:**	No additional information is available for this paper.