Field of a permanent magnet: remotely controlled measurement

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Abstract. In textbooks, magnetic fields are usually visualized by two-dimensional field lines. There, the density of field lines is often misleadingly stated to be proportional to the strength of the magnetic field. This is not entirely correct. To help students better understand the different characteristics of magnetic fields, it is important that they gain experience with magnetic fields by performing real or virtual experiments themselves.

To improve the students’ knowledge of the characteristics of magnetic fields, a remote laboratory was developed which allows exact positioning of a two-dimensional hall sensor around a Neodymium bar magnet. This offers the opportunity to make much more sensitive measurements than it is possible in schools. Technical issues and an example analysis of the measured data are discussed.

1. Introduction

Experiments are an essential component of science and therefore also of science lessons in school [1, 2, 3]. This applies to every kind of demonstration experiment or student activity. While demonstration experiments are usually embedded in a teacher dominated, questioning-developing approach [1, 4], student experiments are often constrained by precise instructions. In theory, instructional approaches that link theory and experiments and engage students actively should lead to a deeper understanding [5]. The way experiments are integrated into the lesson plan determines the learning success [3, 6]. For the development of the learners performance, not only the time conducting the experiment is critical, but so is the total processing time, including preparation and review [3]. However, the large amount of time needed to carry out student experiments reduces the remaining instruction time, which is considered a possible reason [3] for why student experiments do not generally lead to better performance [7].

Participants in in-service teacher training often report the huge amount of time the preparation, installation and execution of the experiments in school take. Furthermore, they claim to have to cope with additional difficulties:

• Costs of apparatus often exceed the budget if specialized topics are being addressed,
• during experimentation (safety) formalities have to be considered,
• in some experiments, due to expensive, sensitive, or dangerous components, students can only be spectators.

A good way to overcome these difficulties is experimentation in remote labs. When expensive, complex, or challenging experimental set-ups are unavailable or impracticable, those labs can
serve as an alternative for promoting practical experimental skill development. Additionally, remote laboratories can also serve as a useful supplement to in-class experiments, when . . .

- the experimental set-up is difficult to implement, time-consuming to arrange, or expensive [8],
- the procedures include dangerous objects, e.g., radioactive substances [8] or high-power lasers [9, 10]
- instrumentation must be shared due to limited lab capacities [8, 11], or
- cannot be provided due to logistical reasons [10], or
- disabled students cannot perform an experimental task due to physical limitations [10].

German students learn about magnetic fields in various classes and at different levels. The analysis of the magnetic field of permanent magnets is often used as a qualitative introduction. A more quantitative understanding of the structure of this field would require either deeper knowledge of electrodynamics (which certainly is not available in schools) or an experimental setting. To measure the field of a permanent magnet accurately, the experimenter has to face several difficulties:

- The experimental setting should be completely non-ferromagnetic,
- the magnetic flux density of the field of a permanent magnet decreases very fast with increasing distance from the magnet. Therefore, a very sensitive hall sensor is necessary,
- additionally, because of this fast decrease a very exact positioning of the hall sensor must be guaranteed.

These requirements make it quite difficult to configure such an experiment for a lesson in school. Hence, an implementation in a remote lab is very applicable. Additionally, conducting the experiment as homework allows to relieve physics in-class teaching by means of a flipped classroom [12, 13, 14]. This would leave more in-class time for a thorough preparation and follow-up.

2. Methods

When planning and developing a remote laboratory there are a number of additional factors that need to be considered, beside the experiment itself. On the one hand, the remote laboratory should be available to everybody at any time and from anywhere. On the other hand, web security measures have to be taken. The experiment should be easily accessible, but the system must regulate access so that only one person at a time is allowed to take control of the experiment. Beside those requirements the system also has to prevent the experiment from being damaged by a (non-)intended user operation. Moreover, the remote laboratory should support access without a previous installation of software since in many schools an installation of new software is undesired. Due to these restrictions we decided to offer access to the laboratory via an HTML5-Webpage.

2.1. The experiment

The user of the described laboratory measures the magnetic field of a cylindrical Neodymium bar magnet. The positioning takes place according to polar coordinates. Therefore, the bar magnet is located in the middle of a round rotatable plate (see figure 1). The two-dimensional hall-sensor which measures the field can be moved back and forth by a linear drive. Stepper motors are used for the precise rotation of the plate as well as for the exact positioning of the linear drive. Around the magnet there is a small area where no measurement can take place due to the physical size of the sensor. The Neodymium magnet is of length 100 mm and has a diameter of 15 mm. It is centred at the origin of the coordinate system; the axis of symmetry of the magnet
is along the $x$-axis of the coordinate system. Building the construction of the experiment, special focus was laid on a completely non-ferromagnetic set-up so that the measurement preferably is not distorted. In addition, the surroundings are also non-ferromagnetic, which would also be difficult to implement in schools.

![Experimental set-up](image)

**Figure 1.** Experimental set-up. The labelled components are (A) rotating plate, (B) bar magnet, (C) two-dimensional hall-sensor, (D) linear drive.

### 2.2. User management

If a user opens the webpage in a browser and requests control the user management system deals with this request—this process is invisible to the user. The implementation of the user management system is done with a MySQL database (see figure 2). When a user requests control over the experiment, the system checks the entries of the database. If the laboratory is not free, the user gets a corresponding message. If it is free, the user gets access to the control unit for a certain amount of time and the system generates an entry in the database, so that no other user can get access to the lab during this time. With every action the controlling user performs on the experiment, the experimentation time is reset and the entry in the database is updated so that no one can connect to the experiment as long as someone is using it. Thus, we ensure that users can start experimentation when the lab is free and also that no one has to interrupt experimentation.
2.3. Control over the internet

If a user is in control of the experiment, the browser sends his or her commands to a PHP script running on a server and deactivates the controlling unit simultaneously (see figure 3). The script now checks whether the chosen location is available and on which path the sensor can get there. If there is a path available, the script sends the necessary commands to the controlling units of the stepper motors and waits until the sensor reaches the desired position. Then, the PHP script sends a confirmation of the arrival at the new position back to the browser which then reactivates the user control and waits for new input.

![User management diagram](image)

**Figure 2.** User management.

2.4. Measurement over the internet

The power supply of the hall sensor plates is a 5-mA constant current source. To guaranty that the supply current through the two hall sensor plates is the same in both plates they were wired in series (see figure 4). For the measurement of the hall voltage, we use two 16-bit voltmeters, which are each connected to the output terminal of a hall sensor plate. Due to technical issues the voltmeters operate in single-ended mode in a range of ±500 mV. In this range 16-bits, corresponds to a resolution of approximately 16 µV, which leads to a resolution of the magnetic flux density of approximately 13 µT. The full measuring range of the magnetic flux density is ±400 mT (for this setting $B \approx 0.8 \cdot U_{\text{Hall}}$). The user can measure the field by clicking on the “measure button”. After this a PHP script again takes action. The script connects to the measurement device, gives the measuring command and then delivers the output of the device back to the browser where it is displayed.

![Control over the Internet diagram](image)

**Figure 3.** Control over the Internet.
3. Results
Besides the previously described measurement value acquisition, the remote lab also offers representations of the magnetic field in the browser. The magnetic flux density is a vector and hence has an absolute value and a direction. To take care of this circumstance the user interface allows a representation of the absolute values of the magnetic flux density as well as a visualisation of the direction plot. As we will see in the following subsections, sometimes it is sufficient to have only one representation, while in general both aspects are necessary to describe the field entirely. It follows an example analysis as it can be done with the laboratory.

3.1. Field on the symmetry axis
It makes sense to start with a look at the behaviour of the magnetic flux density on the axis of symmetry of the magnet. Here because the magnetic field points a given direction, namely into the direction of the axis of symmetry of the magnet only the sign and the value of the field have to be measured. The measurement of the field along the symmetry axis in 10 mm steps leads to figure 5. The diagram shows positive values for the magnetic flux density, so that the vectors all point in the positive $x$-direction. It can also be seen, that there is a fast decrease of the magnetic flux density with increasing distance from the magnet.

![Figure 4. Measurement over the Internet.](image)

![Figure 5. Measured magnetic flux density along the axis of symmetry of the magnet.](image)
3.2. Field along the $y$-axis.

But not only on the axis of symmetry is the direction of the field determined by the symmetry. Furthermore, on the $y$-axis the direction of the field vectors is fixed. Here they point parallel to the symmetry axis but in opposite direction compared to the vectors on the symmetry axis. Figure 6 shows the measured magnetic flux density as it depends on the distance to the middle of the magnet for this case.

Figure 6. Measured magnetic flux density along $y$-axis (flux in negative $x$-direction).

3.3. Field along the line, which bisects the first quadrant

A less simple task is characterizing the field on the line which bisects the first quadrant of the coordinate system. Figure 7 shows the graph of the measured absolute value of the magnetic flux density as a function of the distance to the middle of the magnet.

Figure 7. Measured data along line which bisects the first quadrant: absolute values.
Here, the direction of the field is not clear. It is necessary to offer next to a representation of the absolute values of the magnetic flux density an additional representation, which includes information about the direction of the vector field. The corresponding vector plot is pictured in figure 8.

![Figure 8. Measured data along line which bisects the first quadrant: vector plot.](image)

### 3.4. Conclusion and prospects
The Remote Laboratory aims to help to improve the students’ specialized knowledge of the characteristics of magnetic fields. Furthermore, since the students can perform this experiment at home, it intends to foster their natural scientific curiosity and helps them overcome their inhibitions. In the next semester the lab will be tested with students. Thereby first observations of user activity when working with the remote laboratory will be made. After this testing and improvement period, the lab will be available for public access.

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