Visual Simulation of Electrostatic Field

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Abstract. Electric field and potential are both basic concepts in physics, having a good grasp of the principles of them is of great importance for students major in science and engineer. In this paper, we choose the experiment project of measuring electrostatic field by the analog method as an example to introduce the design of the electromagnetism experiment course. Teaching practice results comply with the New Engineer Disciplines (NEDs). The Instructional design attract students’ interest in physics experiments, achieving the desired teaching results of the electromagnetic experiment course.

Introduction

With the release of Make magazine by Dale Dougherty in January 2005, the maker movement, which originated in the United States, has gradually expanded to be an international phenomenon [1]. The genes of the maker culture coming from the Garage Culture, the Silicon Valley Culture, the DIY Culture and the Hacker Culture, and the maker culture can be concluded as practice, innovation, entrepreneurship, venture capital, creativity, DIY, open source and sharing [2]. Not only in the USA, maker education has gained momentum in College around the world [3].

In 2008, the National Academy of Engineer (NAE) came up with Engineering’s 14 Grand Challenges for Engineering, and later, the Grand Challenges Scholars Program (GCSP) became an expected way of solving the Grand Challenges [4,5]. A very important student competency in the GCSP is ‘Talent Competency: mentored research/creative experience on a Grand Challenge-like topic’ [4]. In addition, the STEM (Science, Technology, Engineering and Mathematics) education, which emphasizes interdisciplinary learning, also plays an important role in GCSP.

Aiming to cultivate more high-quality engineers, China has put forward the New Engineer Disciplines (NEDs) in recent years. The NEDs have the features of leading, blending, innovation, cross-border and developing, which also put higher requirements on students [6]. The NEDs emphasize on practice, which is usually considered as a shortcoming of Chinese higher education, especially engineer education in the past [7].

The maker education, GCSP and NEDs are changing the traditional means and methods of teaching and learning. As we can see, all of them call for the combination of theories, practice and innovation. As a required course of most of the students majoring in science and engineer, Electromagnetism experiment course gives an excellent way of combining theories, practice and innovation. By doing experiment by their own hands, they can have a better understand of physical theories, they can learn how to use their knowledge to solve problems, they can also find and explore new phenomena which can’t be found in textbooks.

However, there are also many problems with physical experiment classes, one of them is the equipment is limited to fixed teaching content and can’t suits student’s needs. Take the experiment of measuring hysteresis loop as example, if the laboratory only offers basic components such as coils, resistor and capacitor, it is nearly impossible for students to finish the experiment by themselves. But if they are offered highly-integrated apparatus, students can finish the experiment by following the instruction manual even though they know nothing about magnetic permeability. We will talk about the other drawbacks of traditional laboratory apparatus in detail later, in brief, we’d like to describe
new apparatus like this: it is well-designed, scalable, and it contains some new technical means by which can students learn more in the process of experiment.

In this paper, we choose the experiment project of measuring electrostatic field by analog method as an example to introduce the design of electromagnetism experiment course. In this case, we designed a set of devices in order to offer a better way to simulate the electric field by experiment. Using our device, they can not only complete the measure of traditional electrodes, but also design and fabricate new electrodes by themselves, which can enhance students' enthusiasm and spirit of exploration. Furthermore, we combined several new technologies with the experiment, by which can we meet the requirements of GCSP and NEDs better.

**Traditional Teaching Content**

**Basic Concept of Electrostatic Field**

The electric field is defined mathematically as a vector field that associates to each point in space the (electrostatic or Coulomb) force per unit of charge exerted on an infinitesimal positive test charge at rest at that point [8]. In the electromagnetic experiment course, students study the relevant properties of the electric field by studying the electrostatic field.

Electric field and potential are both basic concepts in physics, and electromagnetic force is also one of the fundamental interaction.

The electric field $\vec{E}$ at some point in space is defined as the electric force $F_e$ that acts on a small positive test charge placed at that point divided by the magnitude $q_0$ of the test charge [9] (refer with: Eq. 1):

\[
\vec{E} \equiv \frac{\vec{F}_e}{q_0}
\]

(1)

Gauss’s law says that the net electric flux $\Phi_E$ through any closed gaussian surface is equal to the net charge $q_{in}$ inside the surface divided by $\varepsilon_0$ [10] (refer with: Eq. 2).

\[
\Phi_E = \oint \vec{E} \cdot d\vec{A} = \frac{q_{in}}{\varepsilon_0}
\]

(2)

The potential difference $\Delta V$ between points A and B in an electric field E is defined as [11] (refer with: Eq. 3):

\[
\Delta V \equiv \frac{\Delta U}{q} = -\int_A^B \vec{E} \cdot d\vec{S}
\]

(3)

If we draw a line through the points that have the same potential, we can get a equipotential line. According to the definition of potential, we can reach the conclusion that the direction of electric field E is always perpendicular to the equipotential line. Experimentally, electric potential can be measured easily with a voltmeter, so we can know both of the direction and the magnitude of the electric field based on the numerical value of the voltage and the position.

**Experimental Principle**

The experiment of “simulating the electrostatic field with a steady current field” uses conductive microcrystals as a conductive medium, the electrodes are directly formed on the conductive crystallites, and a constant voltage is applied between the electrodes, so that a stable current field is
formed in the conductive medium between the electrodes. The traditional electromagnetic experiment teaching uses the GVZ-3 conductive microcrystalline electric field plotter to simulate the electrostatic field. The device comprises conductive microcrystals, double-layer fixing bracket, synchronous probe. And the upper layer of the bracket is placed on the coordinate paper.

The upper and lower probes of the synchro probe are on the same vertical line, so the trajectories of the two probes are the same. As the figure shows (refer with: Fig. 2-1), when a voltage $U$ is applied between the electrodes, current flows through the electrode plates, and potential equipotential lines are formed between the electrodes. In the experiment, the student measures and draws the potential equipotential line, and then draws the electric field line.

![Figure 2-1. GVZ-3 conductive microcrystalline electric field plotter.](image)

**Disadvantages**

In the process of the course, it is found that traditional methods have certain problems in teaching and measurement.

**First, data collection in traditional device is cumbersome, which is difficult to attract students' interest.** In traditional device, students need to find and hand-paint the equipotential points on the coordinate paper based on the readings of voltmeter. Equipotential points are hard to find but the processing is useless in the teaching.

**Second, traditional devices are prone to errors, affecting the quality of teaching.** Traditional devices use a two-layer probe to draw the measurement point, which will produce the errors on the position between the measuring point and drawing point. And the hand-painted equipotential lines and electric field lines are also prone to errors.

**Third, only limited electrodes can be used in traditional device, restricting students to further study.** In traditional device, the electrodes are fixed on the conductive microcrystals. So students cannot study electrodes other than those provided by the device.

**Methodology**

**Overview of the Solution**

Compared with the traditional electromagnetic experiment teaching methodology, new methodology is asked to mobilize the enthusiasm of students as well as guiding students to explore the experiment and physical phenomena more efficiently. To the case of “simulating the electrostatic field with a steady current field” in this article, teacher put forward these new experimental design goals to realize the above requirements:

**First, electrodes should be easy to make and install.** The electrostatic field model closely relies on electrode, traditional experimental device adopts a method of directly bonding and fixing on the conductive microcrystals when making electrodes, so the types of electrodes available for students to
use are very limited. Students should design and make electrodes independently to explore relevant physical models in the improved experiment.

Second, using computer technology to collect data and visualize it in real time. In modern measurement technology, the application of computer can not only make measurement more convenient and efficiently, but also perform real-time data processing to obtain more intuitive experimental results. In traditional experimental method, students obtain the voltage signal of the measuring point and draw the point by a double-layer probe, which will Inevitably produce errors on the position between the measuring point and drawing point. Improved experiment is expected to collect and process data by computer and present the visualization results at the same time.

Third, using numerical simulation calculation method to obtain simulated electric field distribution to assist teaching. The simulation method need measure and depict the equipotential lines to further draw the distribution of the electric field lines. The result will inevitably contain errors from students' hand-drawn, and it is hard to draw more complex electric field lines. Improved experiment is expected to replace the process with numerical simulations calculation method which can also help student study more complex electric field distributions.

Fourth, using auxiliary measurement methods such as augmented reality. Students should have the necessary understanding of the electrostatic field model studied before the experiment. Improved experiment is expected to introduce visualization techniques such as AR technology into the experimental process to improve teaching effectiveness, stimulating students' passion for exploration.

Device Design

According to the requirements of the teaching objectives, the students should learn to simulate the two-dimensional electrostatic field by drawing the equipotential lines generated by the steady current field, and use this method to improve the experimental device. The experimental device designed is shown in the figure (refer with: Fig. 3-1). Conductive film, electrodes, metal detector, and power supply form the main body of the circuit. Arduino is externally connected to both ends of the circuit to measure voltage and transmit voltage signals to the computer. The resistive screen is attached under the conductive film and connected to a computer for reading the position signal of the test lead. During the experiment, students only need to hold the measuring pen to slide on the conductive film to collect data. Here are the innovations of this method:

![Figure 3-1. Electrostatic field measuring device.](image)

First, replace the double-layer bracket with a resistive touch screen. Resistive touch screen is a sensor that converts the physical position of a touch point (X, Y) in a rectangular area into a voltage
representing an X coordinate and a Y coordinate, thereby transmitting a corresponding position signal. The experimental design replaces the original upper bracket part with a resistive screen. On one hand, it solves the problems that the conventional device is too bulky and the double-layer probe is not accurate enough. On the other hand, it is convenient to perform real-time processing of data on the computer.

**Second, replace the conductive crystallite with a conductive film.** The conductive microcrystals used in the traditional experiments are hard materials, which are not convenient for use with the resistive screen. The experimental design selects the ITO conductive film instead. In the experiment, the conductive film is attached to the top of the resistive screen, and the measuring pen can simultaneously read the voltage information and the position information of the point by contacting the soft film. This method greatly improves the convenience of the experiment. After testing, the parameters of the ITO conductive film finally selected were as follows. (refer with: Table 3-1)

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>300*100(nm)</td>
</tr>
<tr>
<td>Thickness</td>
<td>70(nm) ±0.05(nm)</td>
</tr>
<tr>
<td>Square Resistance</td>
<td>150(Ω/cm²)</td>
</tr>
</tbody>
</table>

**Third, replace the voltmeter with Arduino.** Traditional experiment choose voltmeter to measure the potential. Improved experiment chooses to use Arduino for measurement instead. Arduino is an open source electronic prototyping platform which can be used to implement different functions by assembling various sensors. Arduino is very suitable for students to use. The model used in the experiment is “Arduino Uno”, the measured voltage value can be transmitted in real time with it.

**Fourth, the detachable electrode.** In the traditional experiment, the electrode is directly fixed on the conductive crystallite, and the types of electrodes that can be measured by students are very limited. Improved experiment chooses the thin film of the conductive film instead which is easy to disassemble. To achieve the purpose of replacing the electrode, the student only needs to replace the conductive film with different electrodes. Since the cost of the conductive film is relatively low and the electrode fabrication is simple, students can also design and fabricate electrodes for measurement. This can greatly enhance students’ enthusiasm and interest in exploration.

**Data Collection**

The experiment mainly measures two parts of data: the voltage value of the measuring point on the conductive medium and the position signal corresponding to the point. The former is measured in real time through Arduino. The Arduino converts the analog signal from the measured voltage into a digital signal and transmits it to a computer. The latter is measured by a resistive touch screen which reads the position signal of the test pen in real time and transmit it to the computer. The measured voltage data and position data are processed collectively by the Processing and finally exhibit an electric field distribution. Comparing with the traditional method, new method has a significant improvement in accuracy and convenience. Students are also easy to further process the data on the computer.

**Real-Time Display of the Data**

Based on the convenience of communication between Arduino and the Processing, the experimental interface is developed by the Processing. The experimental interface can display the voltage information from Arduino and the position information from the resistive touch screen, plotting the experimental points in real time. The entire experiment also become more intuitive and vivid on the graphical user interface. Based on the convenience of communication between Arduino and the Processing, the experimental interface is developed by the Processing. The experimental interface can
display the voltage information from Arduino and the position information from the resistive touch screen, plotting the experimental points in real time (refer with: Fig. 3-2). The entire experiment also become more intuitive and vivid on the graphical user interface.

In order to facilitate the experimenter to quickly understand the electrostatic field model and find the equipotential line, we use AR technology, allowing the simulation calculation results to be superimposed on the measurement interface in real time, which is convenient for reference. (refer with: Fig. 3-3) This also encourages students to experiment with their own electrodes, so as to guide them to explore the experimental phenomena and the principles behind them.
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**Advantages and Feedback**

**Advantages**

Compared with traditional experiment, improved experiment has obvious advantages in teaching:

First, the optimization of the experimental process and the introduction of computer technology are closer to the teaching requirements of outstanding talents in the new era. The improve experiment starts from the drawbacks of traditional experiment and focuses on guiding students to explore the physical phenomenon itself in the experiment. The introduction of computer technology has greatly improved the convenience of experimental processing. On the other hand, it is hoped that students will realize the convenience and importance of combining traditional experiments with modern computer technology.

Second, the plasticity of the experimental device and the introduction of reference results provide conditions for further exploration. Flexible device design based on physical principles helps students further explore the phenomenon of electrostatic fields. The development platform or software used in the experimental design, such as Arduino, Processing, Mathematica, are also suitable for students to further self-learning.

**Third, the use of AR technology and the design of graphical interfaces help to enhance students' interest.** The experimental design attempts to introduce AR technology, graphical interface, etc. The goal is to attract more students' interest in physics experiments, achieving the desired teaching results of the electromagnetic experiment course.

**Feedback**

The experimental improvement of “simulating the electrostatic field with a steady current field” is the first step in the design reform of electromagnetic experiment course in high colleges. The improved experiment has been initially piloted at the School of Physical Science and Engineering of Tongji
University with a high praise. Then we intend to redesign and adjust the content of more electromagnetic experiment, aiming to complete a comprehensive curriculum content reform.

Conclusion

This paper proposes a new idea on electromagnetic experiment course design through a case of an improved experiment. We analyze the shortcomings of traditional teaching methods and propose the teaching objectives needed. Based on the computer technology and the new device design, students can learn the physical principles behind the experiment more efficiently. The effect of their ability will be more obvious if students can participate in the design of the entire device. We believe that the teaching ideas presented in this paper will provide great help for the reform of the electromagnetic experiment course in the new era.

References


