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An Active Learning Computer-Based Teaching Tool for Enhancing Students' Learning and Visualization Skills in Electromagnetics

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***Abstract*—Electromagnetic theoretical concepts, which are represented mathematically, are usually challenging to grasp by students. In this study, we explore an interactive technology-based teaching tool to develop further students' mastery of electromagnetic concepts through learning development and visualization of electromagnetic problems. This visualization of the problems will help students analyse, evaluate, and draw conclusions of the impact of electromagnetic-related problems in real-life. The simulation tool in this study is based on a MATLAB® toolbox package, in which partial-differential equations (PDE) solver is the core engine. In this paper, we will also provide a step-by-step guide on the use of such an interactive computer-aided tool so that it can be a great self-guide tool for beginners in the field of physics and a first-level introductory course in electromagnetism. This study will focus mainly on one classical electrostatic problem that is a challenge to students to visualize, analyze and evaluate. Based on students feedback by the end of the course, 80% of students' population are more comfortable with the introduced interactive learning tool.**

***Keywords*—Computer aided tool; e-learning; electromagnetics; engineering education; interactive learning PDE tool**

I. Introduction

ELECTROMAGNETIC (EM) field theory courses are considered very essential building blocks for the students' foundation in Electrical Engineering and are taught in many institutions at both undergraduate and postgraduate levels. However, according to many reported research studies worldwide, students struggle a lot in understanding many important phenomena and concepts in electromagnetics, due to the excessive differential calculus and linear algebra involved and as such students find the subject very challenging to grasp [1]- [2].

In the Department of Electrical and Computer Engineering department at Sultan Qaboos University, two courses on electromagnetics are offered and are embedded within the sophomore and junior levels of the undergraduate curriculum. While the first course focuses on static fields and their effects on various media, the second course is of an intermediate level, covering solutions to Laplace's and Poisson's equations, electromagnetic waves and transmission lines. Students find solutions to electrostatic problems more challenging to visualize and understand, due to the topics being more of a theoretical nature. Furthermore, students' effective learning is not directly related to the setting in a classroom. Thus, modern interactive computer-assisted tools are a necessity.

Traditionally, most of the methods adopted in teaching and learning electromagnetics have focused on teaching EM concepts and the underlying basic mathematical formulations and derivations. However, this classical approach is considered unsuitable anymore in the current century, due to many reasons, including the tremendous applied mathematics with minimal focus on the physical concepts that diminishes the interest of students in such subjects, and consequently the persisting needs for developing students' visualization and interpretation skills to EM problems, especially with the dramatic rise of technology and computing resources.

One of the learning methodologies that can enhance students learning is active learning methods [3]- [5]. Active learning covers all activities that need students' interaction and involvement more than instructors' teaching. Among the active learning techniques that can be implemented in a classroom is introducing problems and requesting students to brainstrom and come up with ideas to solve the problems. It is also essential to keep reminding students to relate the problems to real-world problems. This will show better understanding to the problems. Moreover, interactive-simulation apps are very instrumental in advancing students learning and understanding. Authors in [3] explored an interactive electronic guide as a supplement in teaching problem-based concepts in electromagnetics. Based on the findings from a collected survey, the presented computer based problem-based learning tool has resulted in much improvement in students' learning and understanding to many concepts in electromagnetics.

Various simulation tools are available in the literature and other customized apps can be initiated by course instructors. Many research papers have focused on the development of interactive simulation-based tools in order to boost students learning skills in electromagnetics [6]- [14]. In [6], various interactive software tools in teaching electromagnetic field were developed. The work in [7] presented a simulation tool for the analysis of antenna arrays that can be an effective tool in teaching advanced electromagnetic courses. The research work in [10] developed a simulation-based tool for educational purposes focusing on several classical scattering problems, including scattering by a lossy insulating cylinder. In [14], Sevgi presented a number of powerful virtual simulation

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tools that cover many EM concepts, including plane wave propagation, transmission/reflection of waves, radiation and scattering phenomena.

One more interesting methodology in teaching and learning electromagnetics is the use of multimedia [6], [9], [15]- [21]. In fact, multimedia-based learning methods include use of interactive slides, videos, developing customized learning forms to trigger students' critical thinking and recently the adoption of augmented reality technology in teaching and learning electromagnetism. For instance, focusing on online teaching and learning, also termed asynchronous teaching mode, by developing short videos for delivering lecture materials and tutorials was a practice in many universities worldwide during the current COVID-19 pandemic for over a year now. The use of short educational multimedia allows for more memory recall, increased students motivation and enhanced learning experience. Such multimedia videos do not necessarily need to be lengthy recordings. It is more advantageous to have such educational clips as short as possible to allow for a better memory recall, for instance, in periods of 5 to10 minutes, which will definitely be more attractive to go through by students than watching videos of over an hour duration. Furthermore, the use of multimedia educational videos will be easily accessible by all students and can be watched numerous times at their convenience. The work in [16] introduced augmented reality to aid in learning electromagnetic concepts. The study concluded that introducing augmented reality resulted in enhancing students' learning experience and was effective in learning electromagnetic phenomena. Moreover, the researchers in [19] demonstrated an interactive electrostatic tool using virtual reality. The tool focused on developing a spatial simulation-based active learning environment for students.

The adoption of a face to face laboratory is considered an effective learning tool for teaching undergraduate disciplines, including engineering and science [22]- [27]. Such methodology can accelerate students' understanding of main challenging topics in many electrical engineering , including but not limited to circuit theory, electronics and embedded systems. However, the adoption of laboratory practicals in many universities has been reduced within the last two years, due to the current situation of COVID-19. Further, the cost and lengthy process of preparation and managing large laboratory classes have forced many educational institutions to adopt remote and computer-based learning laboratories.

In this work, we aim to focus on students' visualization skills to classical electromagnetic problems, through an interactive learning process. We explore the use and adoption of one interesting active learning tool from MATLAB, i.e., PDE toolbox, in our first-introductory course in electromagnetics, which is considered a user-friendly package that students will most likely find it convenient to use and learn in a short time without the hassle of going through a lengthy learning process of MATLAB programming. In this education paper, we provide a step-by-step guide in using PDE toolbox in MATLAB for science and engineering students, with more emphasis on electrostatics. The tool can also enhance students learning and visualization skills to magnetostatic problems. Moreover, we aim to analyze and interpret students' feedback and suggestions from adopting this learning technological tool in our third-year course in electromagnetics.

The rest of this paper is organized as follows. In section II, we present an overview of our institution's first-introductory electromagnetics course at our institution with a brief view of the main topics and the intended learning outcomes. Section III presents details and main engines used to solve electromagnetic field-based problems using the MATLAB PDE tool. Furthermore, section IV presents a comprehensive tutorial on the use of PDE app in MATLAB that will be a great complement to learning electrostatic topics. We also developed a google form-based questionnaire in order to collect students' feedback from this active learning task. Based on students' responses, we analyze and discuss them at the end of the course project. Finally, the paper concludes with our findings and remarks from this study.

II. Overview of first-introductory electromagnetic course at Sultan Qaboos University: course topics and learning outcomes

Students at the Department of Electrical and Computer Engineering (DECE) at Sultan Qaboos University need to successfully complete one and/or two courses in electromagnetic field and theory based on their specialization. The first-level course is a core course for all students, at the DECE, which gives students the necessary depth of physics-based problems that are relevant and linked to real-world engineering applications. The adopted textbook for teaching such courses in our department is Elements of Electromagnetics by Sadiku [28]. In this course, students are exposed to electrostatics in free space and electric field effects in other different media as well as magnetostatics. Table. I summarizes the course topics with their suggested pre-requisites.

TABLE I
Main topics and their pre-requisites in early EM course at Sultan Qaboos University.

Course Topics	**Recommended Pre-requisites**
Review of vector algebra	Vector addition, subtraction, and multiplication
Introduction to three-dimensional Collinear Coordinate Systems	Drawing course
Vector calculus	Linear algebra
Electrostatics in free space	Atomic structure of materials
Electrostatic in material media	Microscopic properties of material
Magnetostatics	Electric current and its effects

In principle, the acquired knowledge and gained learning skills that students possess from a particular course are often the required base for other advanced courses. It is worth noting here that by carefully tracking the assessments of a batch of students from particular cohorts, it turned out that this nature of developing learning skills for further advanced courses is missing from many students [29]- [33]. The role of assessment and evaluation to students' learning process has long been adopted and is appreciated by academia and community alike. Keeping that in mind, we

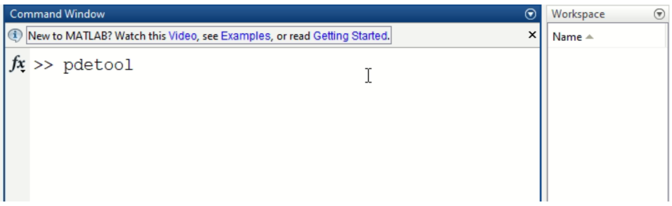


Fig. 1. Screenshot showing one possible way to access the interactive PDE toolbox in MATLAB.

have to develop then the expected learning outcomes for such electromagnetism courses. We summarize below the intended students' learning outcomes, which are matched with the relevant program outcomes:

1) list examples of scalar and vector fields;
2) determine components of a vector field in the direction of another vector field;
3) apply Dot/Cross product between two vector fields **A** and **B**;
4) convert a vector field from one coordinate system to another;
5) apply concepts of vector calculus to solve electromagnetic problems;
6) apply basic electrostatic laws to solve electromagnetic problems in different media;
7) state and describe the physical meaning of Maxwell's equations for electrostatics.

The above list of learning outcomes have been carefully selected based on one well-known learning outcomes framework, that is Bloom's taxonomy [34] and its revision by Anderson *et al.* in [35], which include active measurable verbs that will also help students to focus on to further develop their learning skills. In fact, the presented list of students' learning outcomes, including other outcomes, have been presented and clearly explained to students. Moreover, the learning outcomes keep instructors aim to ensure quality of course delivery and type of assessments needed.

III. MATLAB PDE TOOLBOX: A STUDY GUIDE

Among the very large number of specialized toolboxes in MATLAB is the PDE toolbox. PDE stands for partial differential equations. This PDE toolbox engine is very powerful in solving and providing visualization capabilities to various topics that are useful for students in learning electromagnetics. It is instructive to mention here that partial-differential equaitons-based problems can be solved in MATLAB PDE toolbox using the finite-element analysis. Further, PDE toolbox allows students to import either 2D or 3D geometries.
The toolbox has an interactive user-friendly interface with simple layout. This PDE learning tool can be accessed in MATLAB, in two ways: 1) typing pdetool in the generic command window, or 2) navigating through the App tap and looking for the PDE toolbox, which is illustrated in Figure. 1 by using the command *pdetool*.

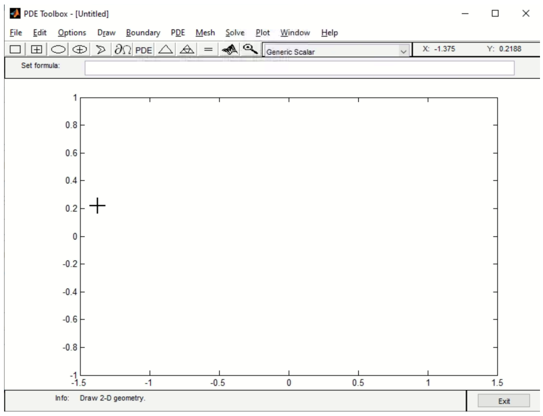


Fig. 2. A screenshot of the user-friendly PDE toolbox interface.

Figure. 2 depicts a screenshot of the MATLAB PDE toolbox. As can be seen, the toolbox allows students to draw two dimensional objects at their convenience that is useful to make models from mathematical electromagnetic problems. In this paper, we focus on electrostatic problems. As such, students can choose from the pull-down menu *electrostatics*. Note that the environment is kept under *generic scalar* mode by default. For a successful implementation and modeling of a particular

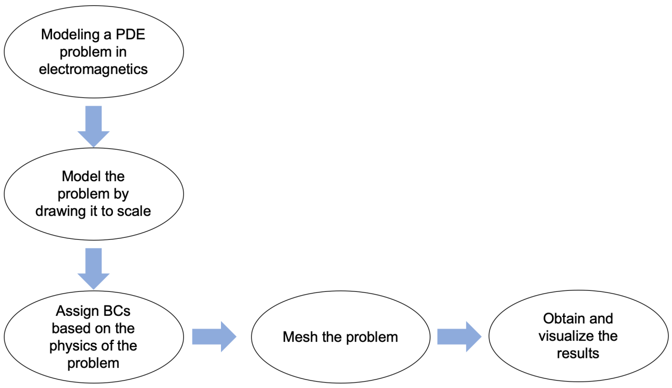


Fig. 3. A generic flowchart showing the main steps that students need to perform while modeling a particular problem in electromagnetics.

problem of interest in electrostatics, students have to be aware of four important steps, that are: 1) choosing the appropriate solver, 2) drawing the problem under study with correct dimensions, 3) assigning the appropriate boundary conditions (BCs) based on the given problem features, and lastly, 4) meshing the problem and obtaining the simulation results. This is summarized in the flowchart shown in Figure. 3. Although steps 1 to 2 are considered easy to learn by students, boundary conditions assignment needs careful thinking from students in order to adhere to the given physics of the problem. Students may encounter difficulties at this stage, however, with more practice, it ends up to be simple to many students. One important thing to highlight here is the nature of the mesh. Students have to keep in mind that initial meshing may not be sufficient enough to ensure accuracy of results to all problems. It is recommended that students practice this meshing feature by refining the mesh for three consecutive simulations and observe the mesh distribution within the modeled problem space as well as observe the change in accuracy of the simulation results. This will enhance students understanding and appreciation to computer simulation tools.

IV. Active learning PDE toolbox in electrostatics

In this section, we explore two interesting problems in electrostatics that many students expressed having difficulties in visualizing their results over the past few semesters. This alternative active learning tool should be effective in boosting students' visualization skills without the need to go through a lengthy learning cycle of MATLAB programming.
In this tutorial, we explore one of the classical problems in electrostatics that many students face problems. Students expressed having problems to write a MATLAB script at early stage of this course, and as such, MATLAB PDE toolbox seems more convenient for students who may find interacting with a screen easy means to learn and develop further understanding of problems in Electrostatics. Further, students have reported difficulties to visualize electric potential in the region inside the rectangular trough.
Figure. 4 depicts the assigned problem to students with the boundary conditions clearly indicated at the walls. In this model, the trough is of size a x b, along x and y directions respectively, where $a = 2b$. The electric potential at the top wall, i.e. $y = b$, is given as V_0, where V_0 can be assigned arbitrary by students.

Given the two dimensional rectangular trough below with dimension of *a* X *b*, where *a* is twice of *b*, use MATLAB PDE toolbox to model the given electrostatic problem with proper boundary conditions assignment and answer the following:
(a) determine the electric potential in the region inside the trough.
(b) Visualize the electric potential inside the trough and interpret the obtained distribution.
(c) Compare the electric potential at the middle of the trough from the PDE toolbox with analytical expression.

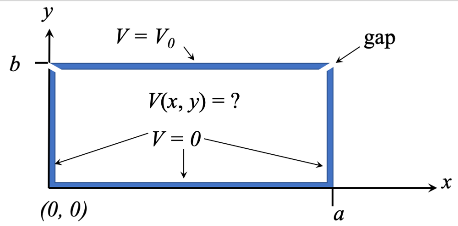
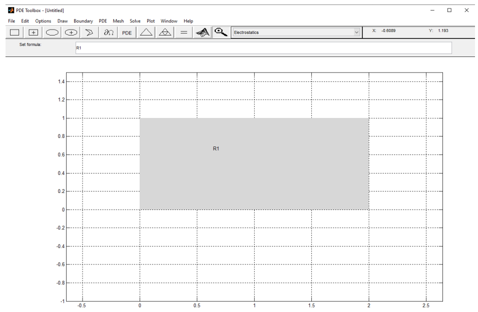


Fig. 4. Assigned electrostatic problem to students. The problem needs from students to compute and visualize the electric potential in the region inside a rectangular trough.

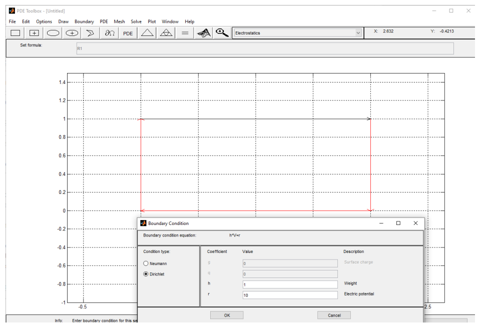
Although an analytical solution to the problem using the separation of variables is possible, students may not be motivated enough to consider solving analytically for unknowns related to electrostatic problems or even writing a short MATLAB script to solve for the same. This is due to the tremendous mathematical derivations involved. However, students can compare the electric potential values at specific points from the PDE toolbox with the analytical ones, where analytical closed forms are available. The closed form expression for the electric potential at any point inside the rectangular trough is given as

$$V = \frac{4V_0}{\pi} \sum_{m=1,3,5,...}^{\infty} \frac{sin(\frac{m\pi x}{b})sinh(\frac{m\pi y}{b})}{m * sinh(\frac{m\pi a}{b})}. \quad (1)$$

Figure. 5(a) depicts a two dimensional view of the modeled problem under study, where $b = 1\ cm$ and $a = 2b$. The following steps are required in order to complete the modeling process of the problem: 1) electrostatics environment needs to be selected and assigned first, 2) then, a rectangle is drawn to scale, 3) after which boundary conditions need to be enforced. Note that walls at $x = 0$ and a, and $y = 0$ are assigned as ground, i.e. $V = 0$, while the wall at $y = b$ needs to be assigned with high potential level, i.e. $V = V_0$ and is assigned as 10 volts here arbitrarily.
Figure. 5(b) shows the activated BCs assignment mode, where student can easily double click on each wall individually and assign the given BC as instructed in the problem. Note that Dirichlet BCs are applied here, since constant electric potentials are kept fixed at the assigned walls of the trough. Once the model is complete with appropriate BCs, it is now



(a)



(b)

Fig. 5. Screenshots showing (a) the modeled electrostatic problem under draw mode, and (b) the model with boundary conditions mode activated, where Dirichlet BCs are enforced at the four walls.

time to apply the finite-element mesh, i.e. 2D mesh, where students can experiment this task in order to observe the accuracy of the results as the mesh is changed. Figure. 6 depicts three different meshes, where the first one shown in Figure. 6(a) represents the initial mesh of the problem, while the second and third ones, (b) and (c) show additional refinement to the mesh, in which the mesh in Figure. 6(c) is more finer than the one applied in Figure. 6(b).
At this stage, student can simulate the modeled problem under PDE toolbox, where one of two options can be selected to generate the simulation results, i.e. clicking on "the equal" sign or selecting solve problem from the solve scroll-down menu. Figure. 7 depicts the electric potential distribution in the region inside the trough, where a 2D contour plot is displayed with

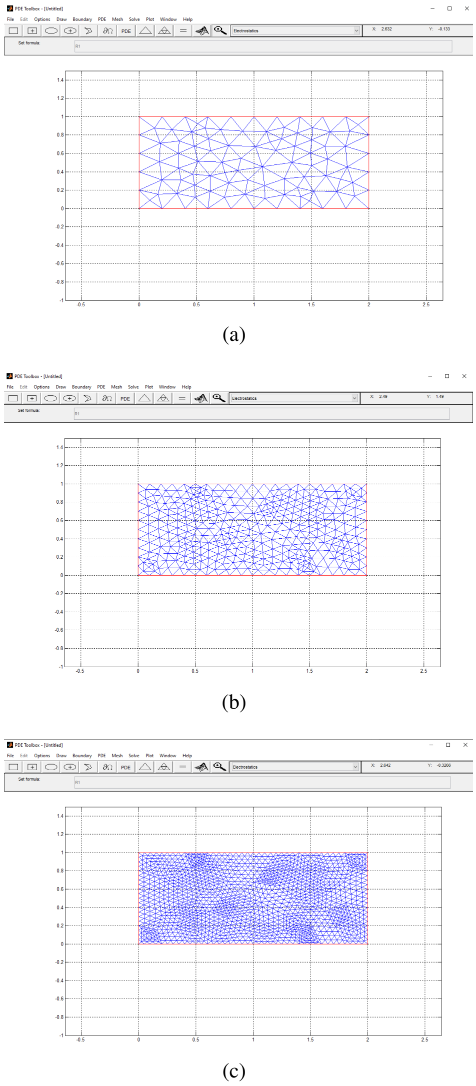


Fig. 6. Screenshots showing three different meshing to the problem using finite-element mesh scheme: (a) initial mesh, (b) single-turn refinement, and (c) second-turn refinement (more finer mesh).

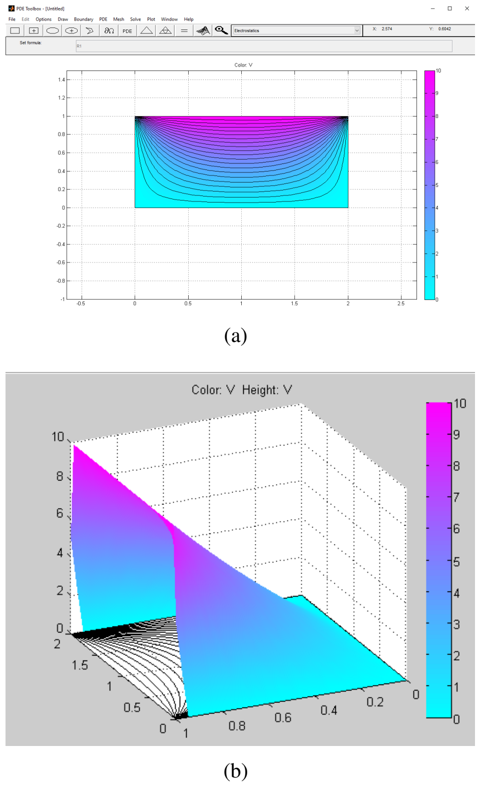


Fig. 7. Screenshots showing (a) 2D contour plot of equipotential lines inside the trough, and (b) 3D view of the same.

10 contour lines as shown in Figure. 7(a), while a 3D view is shown in Figure. 7(b). An interesting exercise for students also is to generate 2D contour plots of electric potential with different potential lines and embedded with electric flux lines. This is presented in Figure. 8, where three contour plots are displayed with different number of contour lines, n = 10, 20 and 30.

V. Analysis and Students Feedback

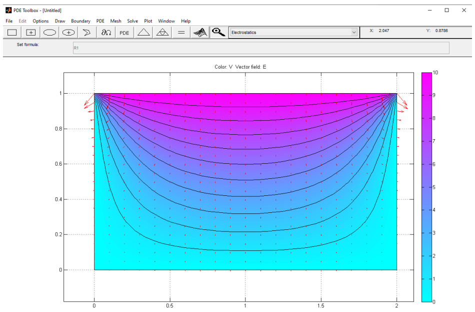
In this section, we present details and statistical analysis from students' feedback on the use of MATLAB PDE toolbox in one assigned project problem in the course. In order to gather students' feedback and comments, an anonymous google form based survey was created, which includes six questions that target mainly students' developed skills and expertise in using the MATLAB PDE toolbox by the end of the project. A population size of 45 students was considered in this study.

It is instrumental to collect students' feedback at the end of the project completion in the course in order to measure the suitability of the proposed teaching tool on students' learning and understanding the course materials. Note that we present the results independently per question. Figure. 9 depicts statistical data from students' responses to their skills level of using MATLAB. Over 70% have confidence of using MATLAB as beginners, while 24% have rated their skills as intermediate and 4% of which have solid skills in using MATLAB.

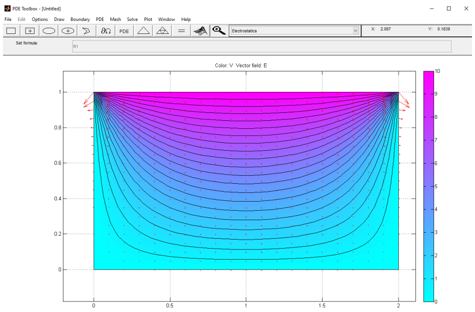
Figure. 10 depicts statistical data from students' responses to the second question, which is related to students' familiarity of using MATLAB scripting. Around 36% have confirmed their ability of writing short MATLAB scripts, while over 60% have difficulties in writing MATLAB codes.

Figure. 11 depicts a pie chart representing students' responses to the third question from this survey. An 80% of total students have indicated their preference of using a friendly interactive package to aid in their understanding to electrostatics, while 20% have preferred learning electrostatics through writing short MATLAB scripts.

Figure. 12 depicts statistical data from students' responses to the fourth question from this survey, which is related to students' skills in using MATLAB PDE toolbox. A 60% of total students have indicated their status as beginner in using MATLAB PDE toolbox for solving electrostatic problems, while 36% have reached an intermediate level in mastering MATLAB PDE toolbox and around 4% believed that they have gained solid understanding and skills in the use of PDE toolbox.



(a)



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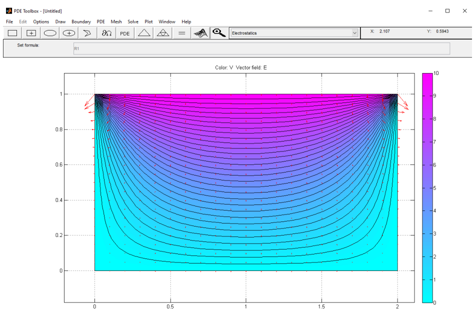

(c)

Fig. 8. 2D screenshots showing three different contour plots of electric potential with different number of potential lines (n): (a) n = 10, (b) n = 20, and (c) n = 30.

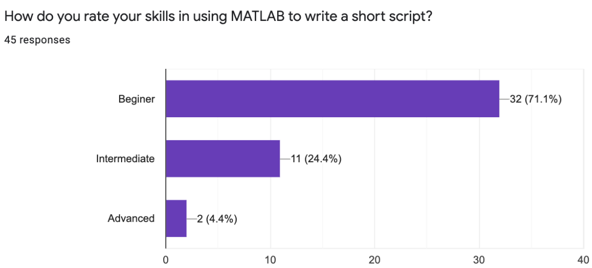

Fig. 9. Students' responses from the first question in the questionnaire.

Figure. 13 shows students' responses to the fifth question from this survey. This question aimed to find out students' ability to solve the assigned project for the course. Although around 60% of total students faced difficulties in modeling the project in PDE package, 30% of them have performed the tasks of the project without any reported challenges. In order to tackle this issue of developing fast understanding of the use

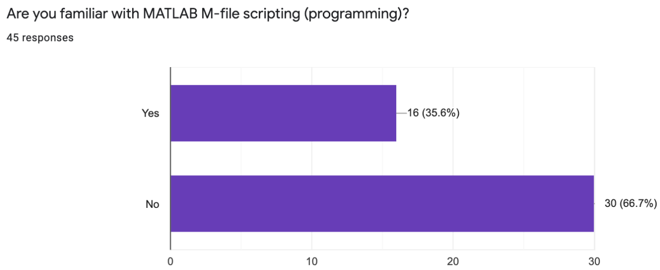

Fig. 10. Students' responses from the second question in the questionnaire.

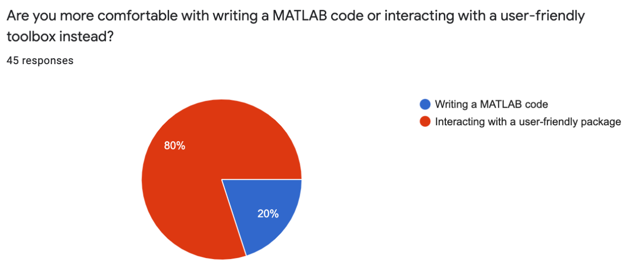

Fig. 11. Students' responses from the third question in the questionnaire.

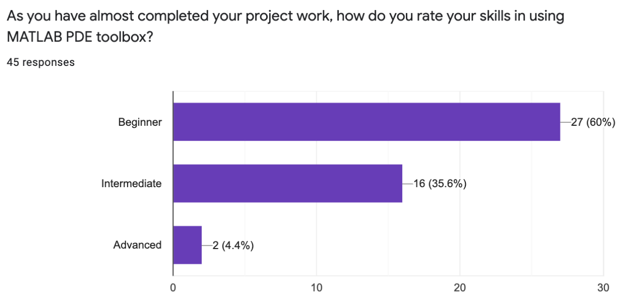

Fig. 12. Students' responses from the fourth question in the questionnaire.

of PDE toolbox, additional tutorial was provided to students, where they have been given the chance to practice a particular problem and model it in PDE tool.

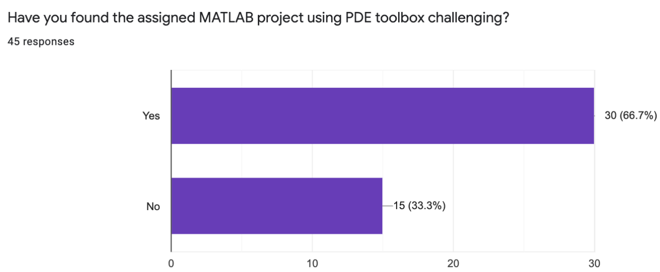

Fig. 13. Students' responses from the fifth question in the questionnaire.

Figure. 14 depicts a bar chart representing students' responses to the last question from this survey, which was related to students' satisfaction from this exercise. Over 60% of total students have indicated that they are able to understanding electrostatics more with the use of PDE toolbox, while 30% highlighted having difficulties in understanding electrostatics with the use of PDE toolbox. This issue can be tackled by giving those 30% of students additional tutorials in order to help them understand the nature of boundary conditions and the applicable solver to use for solving either electrostatic or magnetostatic problems.

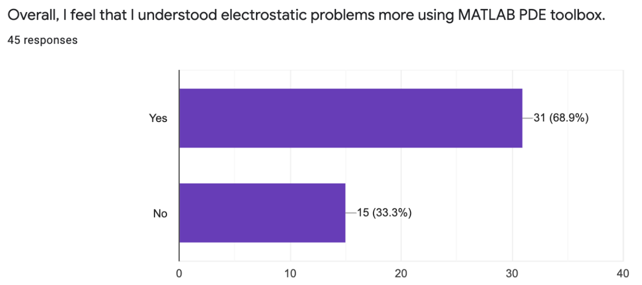

Fig. 14. Students' responses from the sixth question in the questionnaire.

VI. Conclusion

In conclusion, a step-by-step guide on using an interactive computer-aided tool was presented. The tool is based on the MATLAB PDE toolbox, which is believed to be well suited for students taking fundamental courses in electromagnetics theory. The suitability is attributed to the learning cycle, which provides an easy means to learn and develop a solid understanding in visualization of electromagnetic problems as it requires no programming skills from students.

One interesting classical electrostatic problem was presented and comprehensively introduced in the MATLAB PDE toolbox to compute and visualize the electrostatic field (both potential and flux lines) in the region inside a trough. This PDE toolbox can also be applied to more advanced problems in electrostatics and magnetostatics. To ensure the quality and efficiency of the presented guide in the MATLAB PDE toolbox package in solving electrostatic problems, a google-form based questionnaire was developed and provided to students in order to gather their feedback and comments from the assigned exercises. Overall, students have confirmed their satisfaction in using the PDE toolbox, which helped them understand electrostatic problems more easily than solving equations. Furthermore, the integration of this type of computer-based learning guide has improved students learning skills in the use of simulation-based tools.

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