

## 3D Visualization-assisted Electromagnetic Theory Teaching

**Mr. Enrique José González-Carvajal, University of South Florida**

Enrique González was born in Valencia, Venezuela, in 1987. He received his B.Sc. degree in Electrical Engineering from the University of Carabobo, Naganagua, VE, in 2012 and his M.Sc. in 2018 from the University of South Florida. He was an Instructor in the topics of Optical Communications and Guided Waves Systems Laboratory at his Alma Mater until the end of 2014, when he joined the University of South Florida. He is currently pursuing his Ph.D. degree conducting research within the group of Dr. Gokhan Mumcu. His research focus is on the realization of RF reconfigurable devices by using microfluidic technology, specifically filters, RF switches, antenna elements and antenna arrays. He has also developed around fifteen 3D visualizations for enhancing and complementing the teaching of electromagnetic theory in undergraduate courses. The visualizations cover topics of Vector Algebra, Vector Calculus and Electromagnetic Field Theory, Electrostatics and Time-Varying Fields through different interactive animations that can be displayed on 3D-enabled screens.

**Dr. Gokhan Mumcu, University of South Florida**

Gokhan Mumcu was born in Bursa, Turkey, on March 30, 1982. He received the B.S. degree in electrical engineering from Bilkent University, Ankara, Turkey, in 2003, and the M.S. and Ph.D. degrees in electrical and computer engineering from The Ohio State University, Columbus, in 2005 and 2008, respectively. He is currently an Associate Professor at the Electrical Engineering Department of University of South Florida, Tampa, FL. From 2009 to 2015, he was an Assistant Professor at the Electrical Engineering Department of University of South Florida. His research interests are small antennas, engineered materials, THz technologies, and reconfigurable RF devices, antennas and arrays using microfluidic reconfiguration techniques. Dr. Mumcu is the recipient of the 2014 CAREER award from the U.S. National Science Foundation. He is also recipient of 2014 faculty outstanding research award from the University of South Florida. He ranked first on the national university entrance exam taken annually by over 1.5 million Turkish students in 1999. He received the 1999 international education fellowship of the Turkish Ministry of Education. He was the recipient of a best paper award at 2008 URSI National Radio Science Meeting, and the 2008 outstanding dissertation award at The Ohio State University, ElectroScience Laboratory. He served as the technical program committee co-chair of the 2013 IEEE International Symposium on Antennas and Propagation and USNC/URSI National Radio Science Meeting and 2016 International Workshop on Antenna Technology (iWAT).

# 3D Visualization Assisted Electromagnetic Theory Teaching

## Abstract

Electromagnetic (EM) theory education is based on an understanding of numerous mathematical/geometrical operations and their relationships with the physical phenomena. Student success rates in EM education typically get impacted negatively due to a) lack of understanding in the mathematical/geometrical operations and b) establishing the link between mathematical/geometrical operations and the physical phenomena. This paper describes a new teaching technique applied at the University of South Florida (USF) for EM theory education. The technique relies on 3D visualizations presented to students at the Advanced Visualization Center (AVC) at USF that demonstrate the link between the mathematical/geometrical operations and the physical phenomena. Different visualization types such as various coordinates system, vector algebra and calculus, electrostatics and time varying EM fields are presented. Different assessments of student perception regarding the 3D visualizations are carried out by distributing anonymous survey tools throughout three different semester periods. Initial results demonstrate that the surveyed undergraduate population indicates a desire to see more of this type of tools in additional engineering courses and have an overall highly positive perception of the technique.

## I. Introduction

Electromagnetic (EM) theory education suffers from a lack of student interest and learning challenges due to extensive mathematical concepts, operations with geometry and the abstraction of concepts [1, 2]. Different approaches have been proposed to address the challenges, such as hands-on-experimentation [2], the inclusion of computer aided design tools [3] and, more recently, augmented reality (AR) techniques [4]. Recent rise in popularity of 3D-enabled screens and highly improved capabilities of graphical processing units (GPUs), it is now possible to generate complex and real-time 3D visualizations that facilitate teaching of broad scientific topics [5]. Literature survey shows that 3D visualization assisted teaching has been proposed for various fields such as anatomy [6]. However, there are no examples of 3D visualization assisted teaching methods for EM theory. Computer visualization teaching techniques described for EM theory in literature are actually limited to traditional 2D viewing settings (such as MATLAB codes demonstrating EM waves [7] and web-based applications that present concepts such as magnetic fields [8]).

Different than the existing approaches, our goal is to employ 3D visualization of EM fields to facilitate student learning of complex mathematical concepts and several engineering applications of the EM physical phenomena. Specifically, students are presented with custom developed visualization scenes that are rendered in real-time and can be animated/modified on-demand with student/instructor input. These scenes are created in the Autodesk® Maya® software through the development of in-house Python codes that allow for heavy automation of scene geometry creation and animation. One of the main benefits on selecting the Maya® software is that of its native inclusion of Python as one of its main language codes. Additionally, custom Graphical User Interfaces (GUIs) are developed to allow scene manipulation by both

lecturer and students. The 3D Visualizations present animation of complex mathematical concepts and EM phenomena under a panel of 4-by-4 hi-definition 3D-enabled screens located in the Advanced Visualization Center (AVC) of the University of South Florida (USF). The proposed teaching method for the visualization module is by a lecture taught in a 75 minutes session at the AVC (see Fig. 1). This is complemented with an introductory lecture recording that needs to

be seen before arriving to the AVC lecture. The audience present at the lecture can use polarized lenses to fully enjoy these animations just as if they were observing a movie in a 3D-capable theater. This tool aims to allow students to comprehend more fully how electromagnetic fields are distributed in space, the physical and mathematical meaning of vector operations, and their importance as a base knowledge for any electrical engineer.

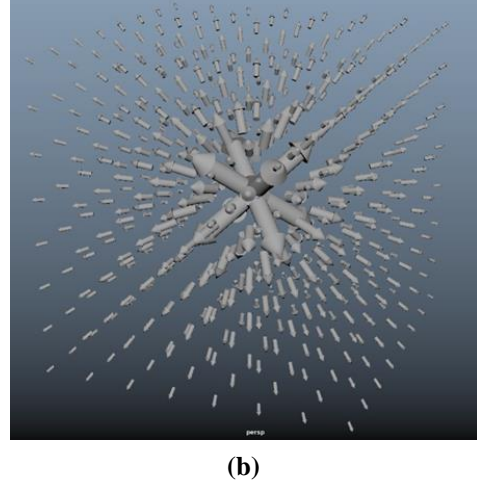
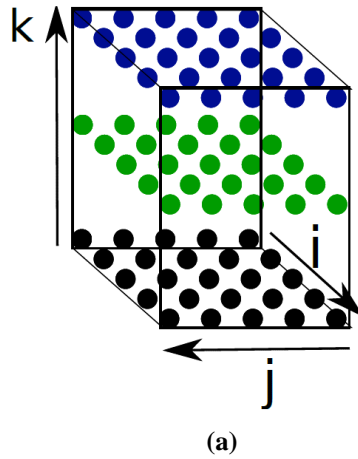
In this paper, the 3D visualizations that are presented to the students are on a broad list of topics ranging from meaning of vectors and basics of vector algebra to the applications of vector calculus in EM phenomena (such as electrostatic fields around charged particles, time-varying fields, and plane waves). The visualizations are fully interactive, allowing the students to observe in real-time how the lecturer can modify the generated scene. It is possible to present geometries from different angles for a better view, or to change pre-defined parameters that introduce changes/animations into the geometries. Additionally, a survey tool is developed to capture initial student perception regarding the inclusion of this technique into the course. This will allow further justification for a more in-depth development of advanced techniques (e.g. more complex visualizations for stand-alone student interaction). The main goals of this paper are: 1) to present the techniques employed in creation of 3D visualizations [e.g. Python codes, interacting the codes with the Autodesk Maya software of the visualization wall, creation of instructor GUI for real-time interaction]; 2) demonstrate the GUI and user scene examples from the developed 3D visualizations; 3) to report an initial survey data collected from students demonstrating their perspectives on this EM theory teaching technique; and 4) to provide a brief discussion on extending instructional functionalities and visualization preparation capabilities by developing new codes that interface commercially available EM simulation tools with the software/hardware of the visualization wall.

## II. 3D Visualization Creation in Autodesk® Maya® Using Python

The computer script developed in Python allows for a streamlined representation of mathematically complex functions in a 3D-environment – enabling the instructor with a tool that brings the textbook functions/formula into the digital domain. The computer script constructs a vector field in Maya®'s 3D-Space by employing the openly available ‘numpy’ library. After importing the library into Maya®, creation of a meshgrid space [see Fig. 2(a)] and linear algebra



**Fig. 1.** Students observing the visualization of EM-wave propagation inside a coaxial cable.

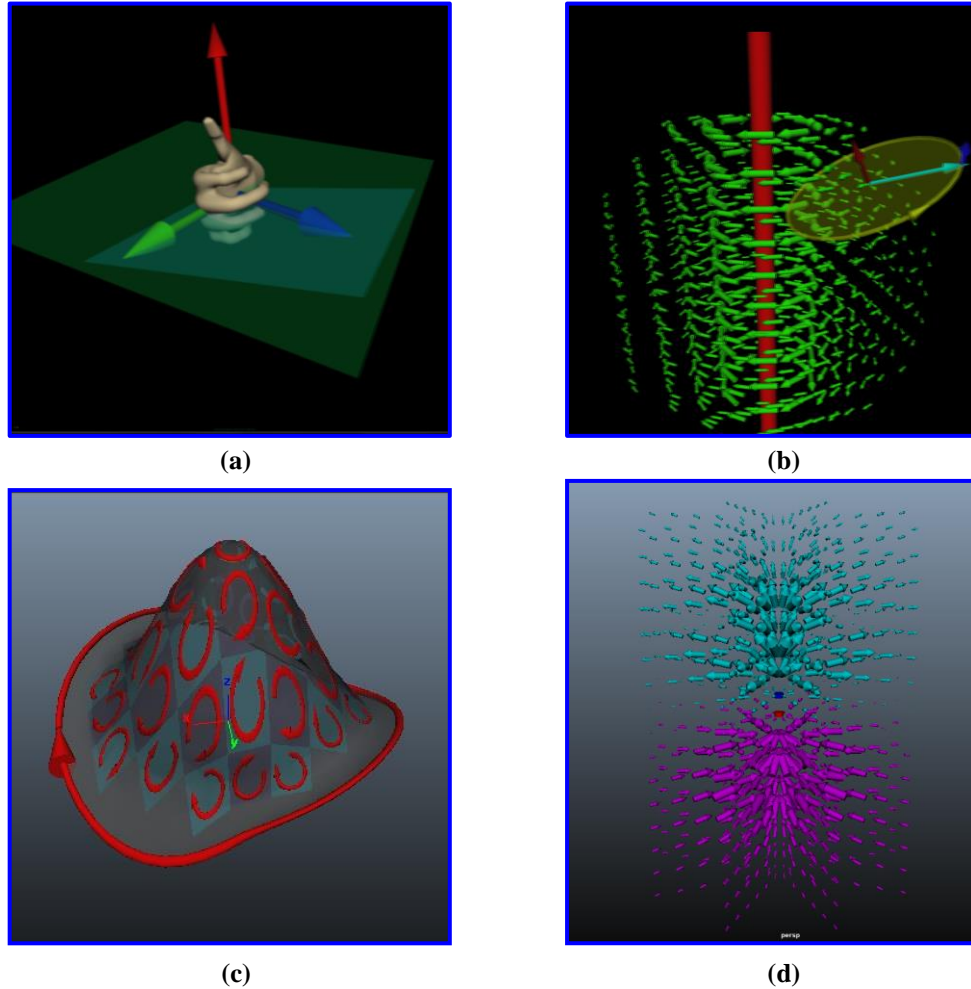


**Fig. 2.** Graphical representation of a meshgrid space (a) and a vector field generated in Maya.

operations becomes possible inside of Maya®. The `meshgrid` function inside the ‘numpy’ library creates a  $N \times N \times N$  matrix that defines the 3D space. The script implements a secondary sub-routine for the creation of vector-like geometries. Specifically, cylinder and cone objects are created in specific points in space defined by a vector field equation inside the meshgrid defined space. As Fig. 2(b) demonstrates an example where the vector field  $\vec{A} = (1/r)^2 \hat{r}$  is rendered in Maya® using the Python script. Python functions enables automation of the drawing process of vector field scene required for teaching EM field distributions.

### III. 3D Electromagnetic Visualizations

The 3D Visualization module begins with the basics of vector algebra: vector addition, dot product, cross product, projection of one vector onto another, and the right-hand rule. This is followed by differential vector operation examples explaining the concepts of gradient, divergence and curl of a vector field. Other visualizations are based on examples that demonstrate the underlying concept of Divergence and Stoke's Theorems. After these vector calculus topics, the module includes visualizations on a broad range of EM topics such as: transverse electromagnetic (TEM) wave propagating across a coaxial cable, an animated particle accelerator model, and plane waves that are incident on semi-infinite dielectric interfaces. The time-varying nature of the TEM wave inside the coaxial cable are generated using the Python script described in above section, while the cable geometry that is superimposed with the TEM wave distribution is created by using the native Maya® tools. The particle accelerator visualization is created using the default tools available in the Maya®. The plane wave visualization is created with an in-house Python code that imports the electromagnetic field data exported from commercially available full-wave EM solver Ansys HFSS into the Python script described in the previous section. This recently developed approach (i.e. interfacing the data exported from Ansys HFSS to 3D visualization scripts/software) paves the way for developing 3D visualizations on more advanced concepts that does not lead to closed-form analytical solutions such as radiation from arbitrarily shaped/customized antennas, propagation in bent waveguides, reflections/scattering of waves from discontinuities, etc. Examples of some of the

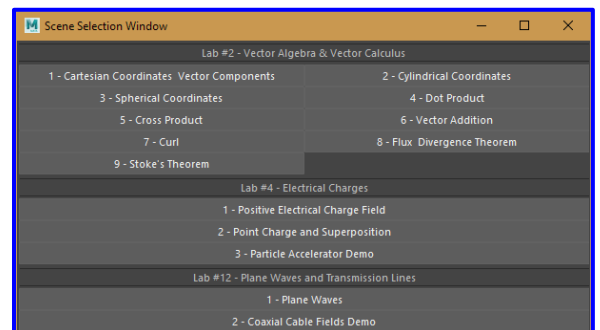


**Fig. 3.** Some of the 3D visualizations developed. (a) Right-hand rule. (b) A rotating vector field and its Curl calculation. (c) Stoke's Theorem representation and Electrostatic field of a dipole (d).

visualizations that were developed are presented in Fig. 3. Specifically, Fig. 3(a) demonstrates the right-hand rule for cross product operations, Fig. 3(b) illustrates the curl of a vector field, Fig. 3(c) provides an interactive demonstration of the concept behind Stoke's theorem, and Fig. 3(d) presents the 3D visualization of the electrostatic field of a dipole.

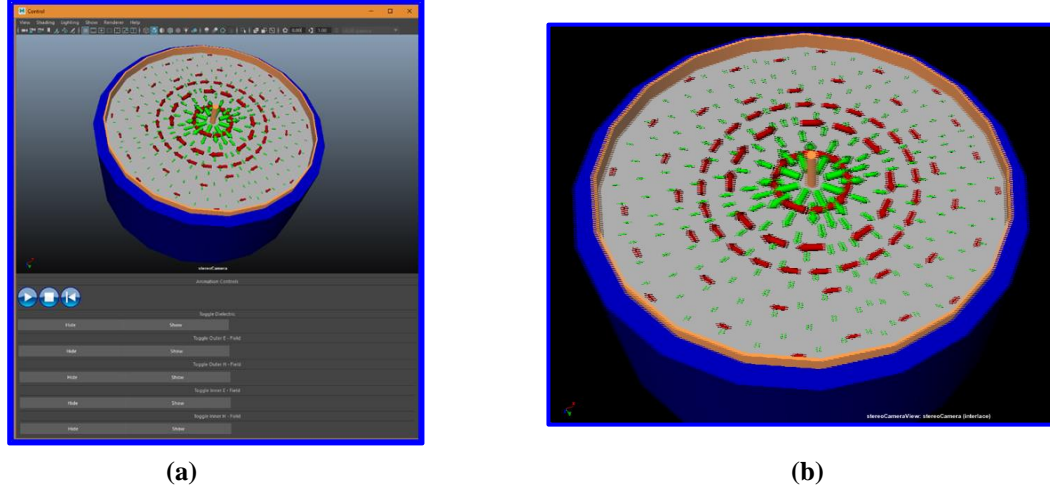
#### IV. Customized Graphical User Interfaces (GUIs) for Scene Manipulation and Animation

A main GUI was created to allow selection of the different visualizations from one stand-alone interface by the instructor (see Fig. 4). Additionally, all 3D EM visualizations included within the module exhibit a customized GUI that simplifies the instructor's interaction with the visualization scene during the lecture. Through the GUI, the instructor enters different input variables during the lecture time (i.e. real-time) to modify the displayed 3D scene for



**Fig. 4.** Scene selection GUI.





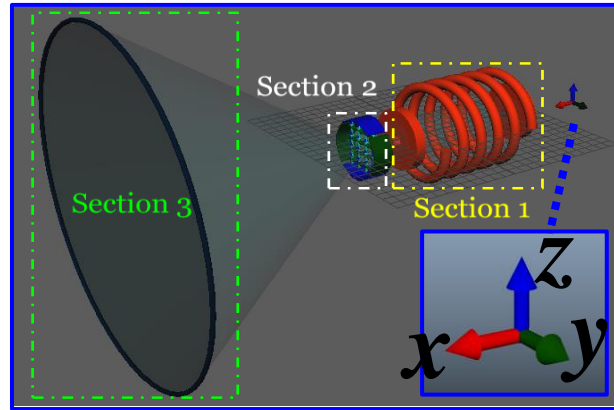
**Fig. 5.** Custom GUI developed for instructor's control and interaction with the scene. The coaxial cable fields scene is shown, instructor UI for scene manipulation (a) and 3D scene for viewing with polarized lens glasses (b).

demonstrating the concept and answer to the questions that may be received from the students. The GUI example for the TEM field propagation in a coaxial cable can be seen in Fig. 5. All GUIs allow the instructor to manipulate the scene view (e.g. rotate, shift, zoom) on demand to provide better explanations to the students.

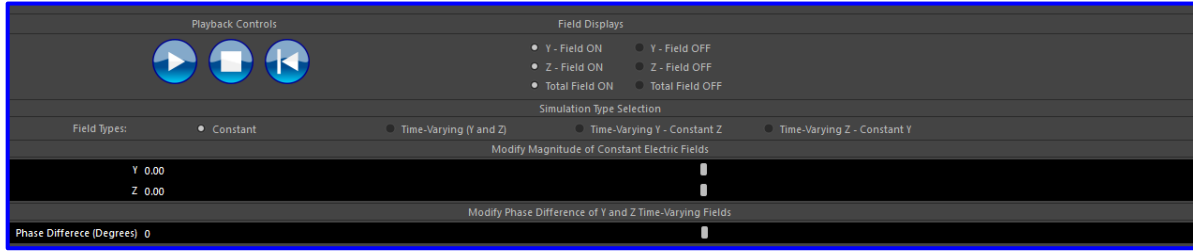
## V. Visualization Examples

### A. Particle accelerator model

The goal of this visualization is to present the students with the effect of electric fields on charged particles. A simple particle accelerator is modeled containing three different sections as shown in Fig. 6. The first section represents an array of plates and coils with the purpose of accelerating the charged particles in the  $x$ -axis toward the second section. The second section is an arrangement of two pairs of parallel plates, which direct the particle beam towards a desired direction. Having two pairs of parallel plates allows for modeling varying fields in two different directions (i.e.  $y$  and  $z$ -axes). Finally, the third section represents the surface where particles collide. With this visualization it is possible to represent the effect of both constant fields and time-varying fields on the moving particles. Fig. 7 depicts the GUI of the visualization. It allows the instructor to start or stop the animation, modify the position values in  $y$  and  $z$  where the particles impact the screen in section 3 and assign time-varying behavior to the electric field components (e.g., constant  $y$  and  $z$ , constant  $y$  and variable  $z$ , constant  $z$  and variable  $y$  or variable  $y$  and  $z$ ). A phase difference can be introduced between the fields of both parallel plate pairs that are in section 2 of the particle accelerator to explain the concept of polarized electromagnetic fields. Fig. 7 shows a

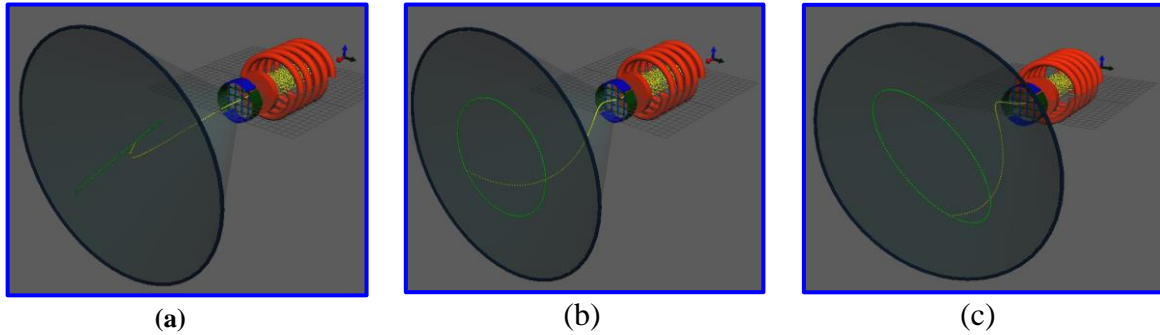


**Fig. 6.** Particle accelerator 3D visualization description



**Fig. 7.** Particle accelerator 3D visualization user interface control

sequence of animations suitable to explain field polarization principles. Fig. 8 (a) demonstrates a time-varying field with components in y-axis and z-axis, both components with equal magnitudes and phases. Fig. 8 (b) shows the trace produced by a time variant field applied in the z-axis and an electric field of the same magnitude with phase difference of  $90^\circ$  applied in the y-axis. Finally, Fig. 8 (c) shows the trace produced by a time variant field applied in the z-axis and an electric field of the same magnitude with phase difference of  $125^\circ$  applied in the y-axis.



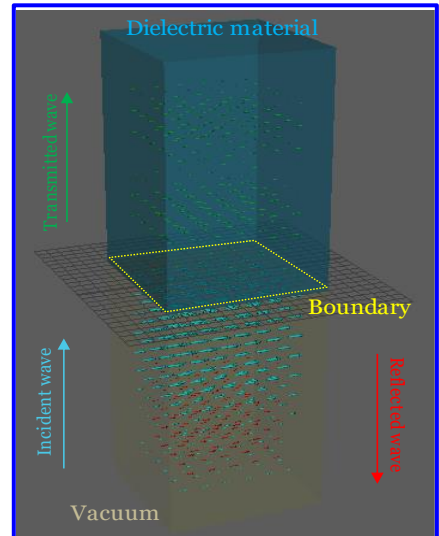
**Fig. 8.** Particle traces due to variant electric fields applied on the parallel plates for various phase difference between the electric fields. (a) Phase difference of  $0^\circ$ , (b) phase difference of  $90^\circ$ , (c) phase difference of  $125^\circ$ .

### B. Plane wave incident on a dielectric boundary at $z = 0$

Fig. 9 represents the visualization environment in which the incident (blue arrows), transmitted (green arrows) and reflected (red arrows) plane waves are shown. Additionally, the visualization app contains an interactive user interface that allows for control on the animation playback, modifying the frequency and wavelength of the incident and the relative permittivity of the dielectric material. As explained in section III, this visualization is generated by exporting fields of commercially available full wave EM solver Ansys HFSS and importing into the Python scripts.

## VI. Results and Discussion

The Vector Algebra and Vector Calculus, along with the EM waves inside a coaxial cable Visualizations were developed and administered to the EM course of the Fall and Spring semesters of 2016 and 2017 respectively. After Spring 2017, curriculum changes in at USF replaced the EM undergraduate course with the Electrical Engineering (EE) Science II course. The course



**Fig. 9.** Plane wave incident on a dielectric boundary at  $z = 0$  - 3D visualization description

includes a 1 credit lab component (about a total of 10 labs per semester) and 3D visualization related activities are planned to be utilized in 3 labs. In addition to the 3D visualizations demonstrated to the EM course, the particle accelerator and plane wave 3D visualizations were developed primarily for the undergraduate level EE Science II course. These courses correspond to junior-level courses in our institution. The sessions complemented the knowledge acquired in the classroom with the introduction of 3D visualizations that stressed the applications, importance and key characteristics of such concepts.

To assess the student perception of the 3D visualizations, a survey was developed and administered in-class for the EM course of Spring 2017. Five different questions were asked as seen in Fig. 10 and 11. The answers to the questions shown in Fig. 10 were scaled from 1 to 10, with 1 being the lowest score and 10 the highest. The survey was distributed among a total of 17

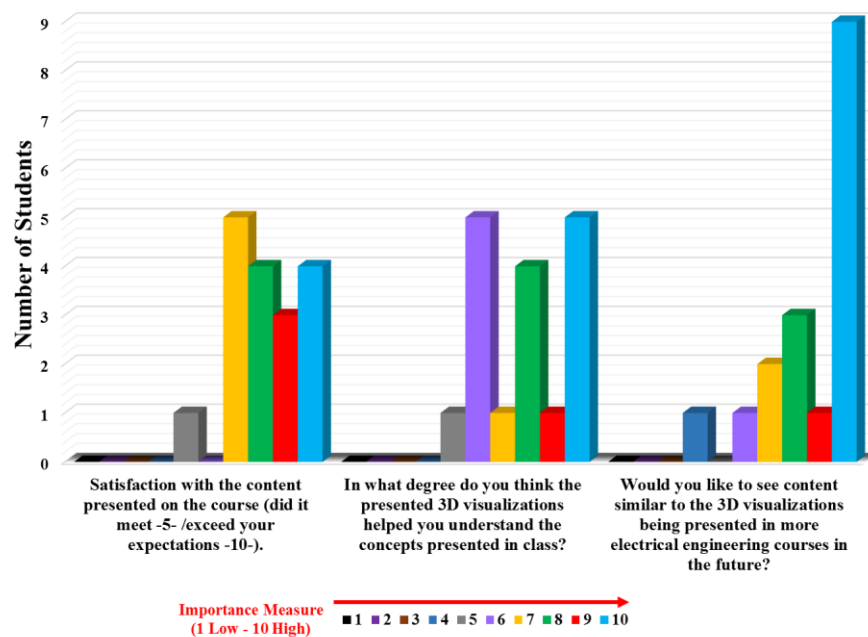


Fig. 10. Survey data from students participated in Spring 2017.

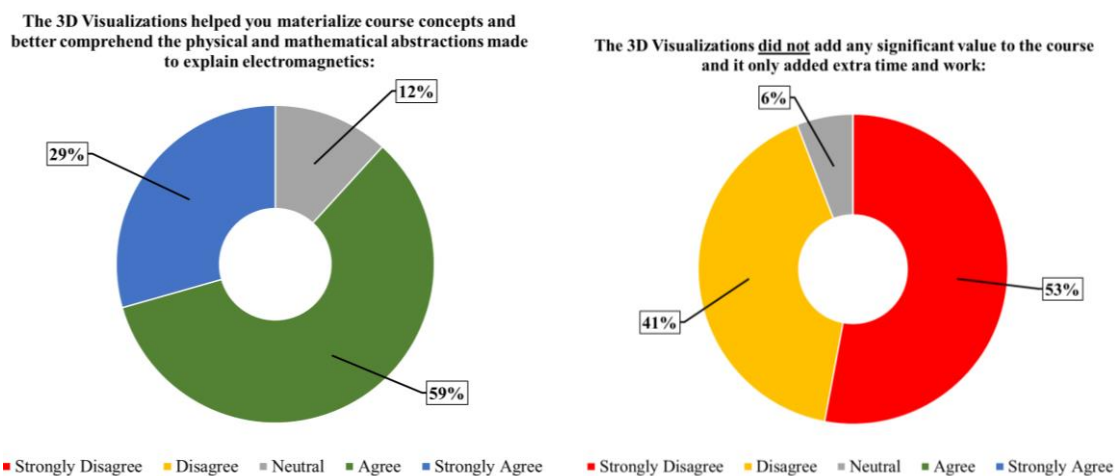
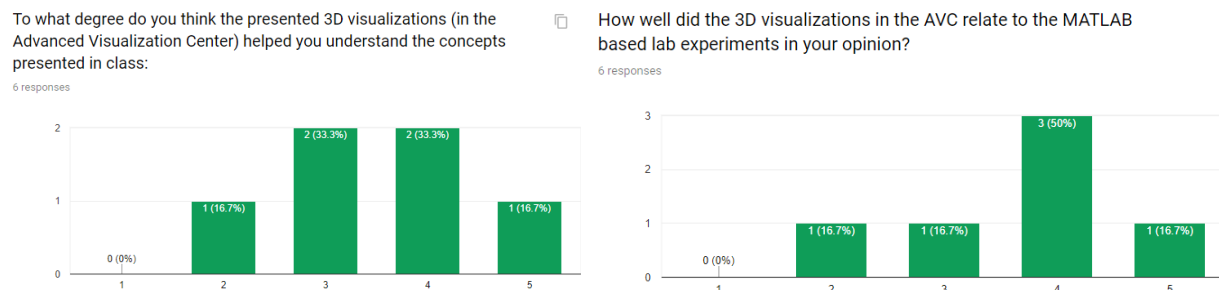


Fig. 11. Survey data for the students that participated in Spring 2017.



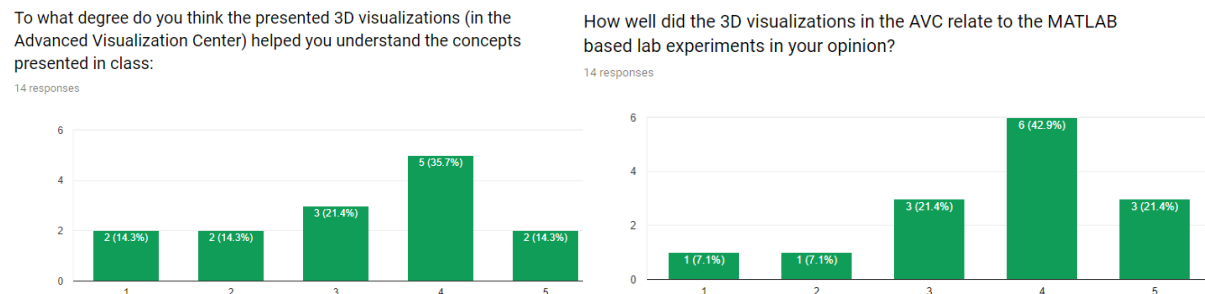
students that assisted to the special recitation sessions. The students that were given the survey correspond to the group that attended the final in-class recitation session of the semester. The students indicated measured values above 7 points among almost 90% of the surveyed population when asked about how they perceive the course content. They found the 3D visualizations to be useful to promote understating of the concepts with at least 60% of the surveyed students indicating a level of 7 or above. It was a consensus among more than 80% of the students that they would like to see tools like this included in other engineering courses such as physics, semi-conductors, electronic materials and calculus. Fig. 11 corroborates that over 59 % of the students agree and 29 % strongly agrees with the positive added value of the 3D visualizations to the course. Additionally, at least 53 % of them indicate a strong disagreement and 41 % disagree when asked if the 3D visualizations add irrelevant and time-wasting content to the lectures.

Fig. 12 and 13 show the questions and results to the survey administered to the Fall 2017 and Spring 2018 students of the EE Science II course respectively. This time the survey was conducted through an online service and student participation was considerably lower than the in-class survey. The survey of Fall 2017 was sent to 20 students and only 6 replied. The survey of Spring 2018 was sent to 50 students and only 14 replied. As it is seen in the results at least 50% of the students that took the survey found the visualizations particularly useful for improving their understanding of the concepts delivered at the lectures. Additionally, over 60% of the surveyed students were able to connect the concepts explained in the visualizations with



**Fig. 12.** Survey data regarding student satisfaction and impressions on the 3D visualizations applied to the EE Science II course. Results for Fall 2017.

the experiences performed in the laboratory.



**Fig. 13.** Survey data regarding student satisfaction and impressions on the 3D visualizations applied to the EE Science II. Results for Spring 2018.

## VII. Concluding Remarks

A new teaching technique for enhancing student understanding of EM phenomena and its associated mathematical formulations has been developed and implemented at the University of South Florida. Although the visualizations are presented to the students in a specialized 4x4 visualization panel in our institution, they can be presented in any 3D-capable monitor with a computer running the Maya® software. Initial surveys among students have demonstrated on average over 60% satisfaction among the surveyed population regarding the concepts presented within the 3D visualizations. Additionally, majority of the students have expressed their desire to see further tools like this developed for additional engineering courses. Further controlled testing is required to accurately assess the impact of these tools on student performance. Additionally, online testing proved to offer low student response as compared to the in-class survey. Future surveys are planned to be administered in-class during the final lecture of the semester to increase student participation. Further in depth-studies on impact of student learning with these tools are planned but additional and suitable funding is required to provide full-time dedication to this project. With the arrival of cost effective augmented reality devices [i.e. virtual reality (VR)] it could be possible to implement this kind of tools in stand-alone devices that allow for direct student interaction with the presented concepts and 3D visualizations.

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