The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #43060

Enhanced Learning by Visualization Applying Embedded Hands-On in Electromagnetics Class

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Introduction

This paper examines enhanced learning through visualization and hands-on experience in the Electromagnetics course in the ECE curriculum. Learners often encounter difficulties in connecting one class to another within the Electrical and Computer Engineering curriculum. Many ECE students sense a knowledge gap or an overwhelming feeling of inability when dealing with mathematics or certain rigorous topics. Electromagnetics is one of the courses that present these challenges [1], [2]. This paper introduces newer approaches, demonstrating how embedded hands-on experiences provide visualization and enhance the students' learning process First, authors from two different institutions identified gaps in curriculum continuity, specifically considering the electromagnetic course. The authors then conducted a survey that included questions about students' 1) prerequisite courses and readiness, 2) confidence levels before starting the course, and 3) connections between formal experiences and Electromagnetics. Second, the authors extracted common challenges and emphasized the importance of visualization in Electromagnetics, which represents typical courses that require students to engage with abstract mathematics while studying invisible light and its properties. Lastly, the authors summarize the educational benefits of embedding more visualization and hands-on activities, which enhance students' learning in the Electromagnetics course, while also considering continuity and its curriculum.

Motivation and Challenge

Authors obtained the collaboration opportunity from the Air Force Academy's summer faculty research program with LeTourneau University's participation. The authors identified common challenges in Electromagnetics course at each university, both of which are focused on undergraduate education. The authors from LeTourneau University had the opportunity to visit and audit the learning environment at the U.S. Air Force Academy, conducting interviews with faculty and students there. Electromagnetics is one of the targeted courses studied by the authors, referred to as "Introduction to Electromagnetics" in the U.S. Air Force Academy and as "Electromagnetic Fields and Waves" in LeTourneau University.

Identification of Gaps in Curriculum Continuity

The U.S. Air Force Academy and LeTourneau University, while attracting a different cohort of students, are similar as undergraduate teaching schools, facing common challenges. Electrical and Computer Engineering (ECE) is recognized as a difficult major and is not a popular choice among students at both universities. It has been a challenge both to recruit and to retain electrical engineering students at both universities. Even among students who choose ECE majors, there are frequent cases where they drop and change their majors when facing difficult topics and classes in the ECE curriculum. The authors chose to focus on Electromagnetics, one of the core courses in the ECE curriculum common to both schools. Another reason is that the two primary authors conducting this research have served as primary instructors for this course for many years. This course is recognized as an upper-level theory-based foundational course, on which courses like Advanced Electromagnetics, Transmission Lines, and Antenna Design, may be based. Electromagnetics is considered the most difficult course in the ECE curriculum for several reasons: (1) It requires the most difficult mathematics.(2) It is highly intuitive, even more so than Electric Circuits. (3) None of the major concepts (charge, force, electric field, magnetic field, electromagnetic waves) are visible. These difficulties can be exacerbated or alleviated depending on where this course is placed in the curriculum. U.S. Air Force Academy places a separate connecting math course as an ECE version which is compatible with the U.S. Air Force Academy's engineering math course (Math 346) in the junior year fall semester to cover foundational components in Math along with the ECE perspective [3], [4]. In this approach, the Electromagnetics course at U.S. Air Force Academy follows in the junior year spring semester, ensuring that the course is well aligned with the formal math course. LeTourneau University, on the other hand, places the course in its senior year which provides a two-year gap from their prerequisite math courses before directly applying those topics in the Electromagnetics course [5]. Students expressed two typical difficulties: 1) They do not remember much of what they learned, and 2) They are not exposed to where they should apply the math.

Electromagnetic Course Difficulty: A Mathematical Perspective

For both universities, students often express difficulty dealing with certain mathematics in the ECE major. Electromagnetics requires a great deal with lots of math requiring the student to deal with material from Calculus III, Differential Equations, and Physics II containing multivariable integrals, divergence, curl, coordinate systems, and complex numbers to represent the invisible waves. Students are aware that Electromagnetics is different from other ECE courses such as Electric Circuits and Digital Electronics because the topics cover imaginary and invisible concepts of the electromagnetic wave and its distribution in space. The following student survey results in Fig. 1 and Table I illustrate the challenges addressed above. The survey was conducted at LeTourneau University in Fall 2023, and the survey questions were asked to hear the students' own views and status regarding prerequisite courses. Questions dealt with 1) Prerequisite Courses and their Readiness, 2) Confidence levels before starting the course, and 3) Connections between formal experiences and Electromagnetics. Students participating in the survey confirmed that the formal math and physics courses are important to comprehend and learn Electromagnetics. However, the scores for applying formal math and physics knowledge to the Electromagnetics course, as well as confidence levels in using it, were relatively low. Another survey assessed the usefulness of introducing fundamental math tools at the beginning of the course, indirectly addressing students' math challenges and needs. Fig 1. displays survey statistics from Fall 2023 at LeTournea University, where 14 students rated statements on a scale from 1 (strongly disagree) to 5 (strongly agree). Table I presents the survey results, including average scores and standard deviations. It highlights both the importance and challenges of the language of mathematics in students' learning. The data reveals that students perceive mathematical language as crucial but also difficult to grasp, indicating areas for potential improvement in teaching methods or curriculum design.

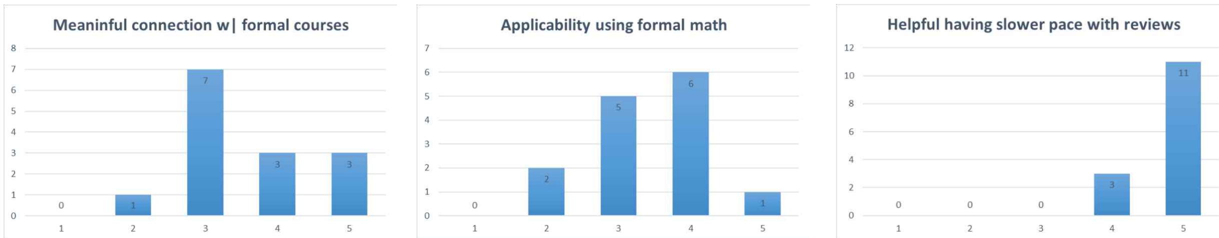


Figure 1. Survey Results of course connection, applicability, and necessity of review

Table I. Students Survey Results about Math & Course Review

Survey Question Total (14 students in LeTourneau University Fall 2023)	Average	Standard Deviation
The formal mathematics courses helped me make meaningful connections between mathematical theories and electromagnetics applications	3.57	0.90
I found it easy to apply mathematical concepts learned in formal courses to solve electromagnetics problems	3.42	0.82
Was it helpful to review and cover vector analysis and coordinate system (Chapter 1) with a slower pace	4.78	0.41

Extraction of common challenges

The authors also reviewed course evaluations from previous years of the Electromagnetics course, where students provided feedback, including requests or compliments regarding the significance of visualization in the course. Table II contains comments from students' formal course evaluations. The selected comments in Table II highlight three typical areas that the instructor should consider improving for students' learning experience.

Table II: Challenges in Three typical areas with formal students' comments

<u>Curriculum Continuity & General</u>
"Fields and waves is well known for being a difficult class" "It could be beneficial to move Fields and Waves earlier in the course sequence, closer to when Physics II and Calculus III are being taken, so that there's not as much of a learning curve. If Fields and Waves is broader than Circuits, why does Circuits get taught first?"
<u>Emphasis of formal math and science courses</u>
"Review Calculus III, most of the course is based on this and if you understand those concepts very well you won't have to waste more time relearning it." "Review your Physics II before you start the class." "Do well in University Physics 2"
<u>Needs for Visualization</u>
"Bringing more visualization would be helpful." "I would have preferred more visual aids, specifically animations of the fields."

Conditions and Constraints in Class Environment

The class environment plays a pivotal role in fostering effective learning and holds significant importance in shaping the educational experience for students. It is useful to clarify the class environment for both universities along with the constraints so that it reflects better how visualization tools and trials work. Both institutions adopt typical university classes and semester systems. However, the U.S. Air Force Academy has a unique identity as a military school, while LeTourneau University has a distinctive identity as a private Christian university. With these unique identities, the authors emphasize the importance of embedding institutional identity and mission into class design along with considering curriculum and holistic university mission [6]. The authors list the essential components to set course environment in Table III. The authors consider the structural setup to determine which visualization or hands-on activities are more appropriate for effectively embedding those modules.

Table III. U.S. Air Force Academy and LeTourneau University's Electromagnetics Course Environment

	U.S. Air Force Academy (Spring Semester)	LeTourneau University (Fall Semester)
Course Name	Intro. to Electromagnetics	Electromagnetic Field and Wave
Class size (# of students)	10 ~ 15	7~ 15
Year in curriculum	Junior	Senior (Junior + Senior in 2023)
Classroom setup	Projector, Whiteboard Laptops	Projector, Whiteboard, Some (Laptops)
Class time	53 min, total 40 class modules per semester	80 min, twice a week, total 29 class
Class Structure	3 credit hours	3 credit hours ▪ 5 min Devotional ▪ Two 40 min sections with 3~5 min break
Class Contents (Topics may vary)	▪ Vector Analysis (Transmission Line Theory) ▪ Coulomb's law and electric field intensity ▪ Electric Flux Density, Gauss's law and Divergence ▪ Energy and Potential ▪ Conductor and Dielectrics / Capacitance ▪ The steady magnetic field ▪ Magnetic forces, materials, and inductance (S parameter) ▪ Time-varying fields and Maxwell's equations	

In response to the challenge of maintaining continuity between the electromagnetics course and its related prerequisite mathematics courses, LeTourneau University ECE department decided to move the electromagnetics course from the senior to the junior year, advancing it by one year starting from the Fall of 2023. By running the course in a setting where both juniors and seniors take it together, the authors have a unique opportunity to compare their achievements and analyze any correlations between their performance and the course sequence. Typical and common constraints also exist in both universities which can be applicable to other universities. The authors interviewed and listened to other faculty to reconfirm that time is one of the most important constraints in their teaching. In this interview, instructors not only in Electromagnetics but also in other courses usually experience a lack of time to cover all the planned topics. Specially, the U.S. Air Force has a specialized curriculum to achieve both academic and military standards in its education, and the total in-class and out-of-class time seems limited compared to other universities. Therefore, careful and effective class design is highly important to consider this time constraint. For both universities, there are no separate times for the labs in Electromagnetics course. Therefore, adding more materials and activities is usually challenging without a designated lab time. Another challenge at U.S. Air Force Academy, is that the Electromagnetics course is targeting senior year students with their usually busier schedule including many other time-demanding situations such as job seeking etc. Last, it is ideal that the course provides the balance of covering theory, simulation, and measurement. This is generally true not only for any engineering course but especially Electromagnetics.

In light of these constraints, the authors focused on the following questions to address the apparent difficulties:

(1) “How can we introduce more visualization of invisible Electromagnetics, which includes difficult and abstract mathematical expressions and concepts?"

(2) "Can a hands-on approach using simulation, measurement, and calculation tools help students learn the materials more effectively?"

(3) "How can two related courses be redesigned to incorporate more cohesive and sequential elements between them?"

Pedagogical Methodology

The importance of visualization in effective student learning has been addressed and emphasized [10]. In the Electromagnetics course, there have been attempts such as PBL (Project Based Learning) [11], Hands-on and labs [12], [13], Visualization using software [14] – [18], demonstrations adopting affordable equipment [19] – [22] to enhance students’ learning experience. The authors redesigned courses related to the target course to include three major components in engineering practice: theory, simulation, and measurement. Additionally, the authors adopted open-source educational resources and simulators to incorporate hands-on labs with enhanced visualization. Another approach was to introduce connected topics from the related courses or areas in electromagnetics. Topics of basic RF and VNA measurement can be embedded into the target course to add more hands-on practice to connect applications. The authors also carefully considered the possible shortage of class time when applying more hands-on activities in its integration rather than adding extra work. The authors utilized tools such as time segmentation techniques and provided guided handouts to blend teaching components and maximize students’ learning. For a given target course, the authors address the following outcomes and conclusions: 1) Analysis for current learning environment 2) Identification of barriers and consideration of various pedagogical approaches 3) Identification of 'priority of contents and outcomes' in the course 4) Design of pilot modules to overcome known challenges 5) Application of a holistic approach to create a more connected and cohesive course within the existing ECE curriculum and program. The authors conclude that hands-on activities with visualization and integration of connected topics promote more active learning which is assessed by students' progress in learning and feedback regarding newer trials compared to formal class practices.

Importance of visualization in Electromagnetics

The authors applied two main visualization approaches. One is the full wave simulator to visualize both static and time- varying electromagnetic fields. The other is a hands-on approach using VNA to characterize the devices. This kind of approach should be well designed and combined with the theory. With the legacy of LeTourneau University and more resourceful conditions of the U.S. Air Force Academy, instructors could apply well known tools for the course not only for visualization, but also for experiencing tools from the real world industry environment. In this way, the single course can cover the subject with all three relevant areas in the EM course (theory, simulation, and measurement). The following describes the visualization tools used in the course. The authors first listed the modules and corresponding topics as a preliminary work to map the current course. Then, the authors considered the most relevant topics and less important topics to plug-in or embed corresponding visualization and hands-on activities. It is inevitable to drop a certain amount of content, however, the authors try to keep the contents and design carefully to introduce the tools without losing much theory and still covering topics. The following shows how authors embedded the materials rather than just adding the materials.

Course Module Design and (Re) Arrangement

The simulation assignments were assigned with the corresponding theories in the lecture as a parallel learning. A few are covered as term projects as well. Fig. 2 and Fig. 3 show the excerpt of module planning with simulation module to apply Intro. to Electromagnetics (ECE 343) course of the U.S. Air Force Academy. Course analysis is conducted to list the current topics and the sequence along with the textbook topics. In Fig. 2, lecture contents are listed to confirm the core topic and elements from the switching order rather than following the textbook order with the instructor's effectiveness to teach. Current slide and lecture notes are reviewed with the originally designed teaching order as providing covering topics and its sequence. This provides preliminary design and course flow so that instructors investigate rooms to introduce more visualization and hands-on.

Electromagnetics Vol. 1	Covered	Partially Covered	NOT Covered
Contents		University A Selection	
1 Preliminary Concepts	1.1 What is Electromagnetics?		1
	1.2 Electromagnetic Spectrum		4
	1.3 Fundamentals of Waves		3
	1.4 Guided and Unguided Waves		2
	1.5 Phasors		5
	1.6 Units		NOT Covered
	1.7 Notation	Lesson 1	NOT Covered
2 Electric and Magnetic Fields	2.1 What is a Field?		6
	2.2 Electric Field Intensity		7
	2.3 Permittivity		8
	2.4 Electric Flux Density		9

Figure 2. Analysis for course module and sequence

Fig. 3 shows the class activity map which shows the in-and-out classroom activities for the course. These module navigation map and class activity mind map help authors to consider which class module and timeline are feasible and efficient to embed visualization and hands-on modules. Both the U.S. Air Force Academy and LeTourneau University already practice typical classroom setup which may include course components such as lecture, quiz, class demo, hands-on, and other outside of classroom activities.

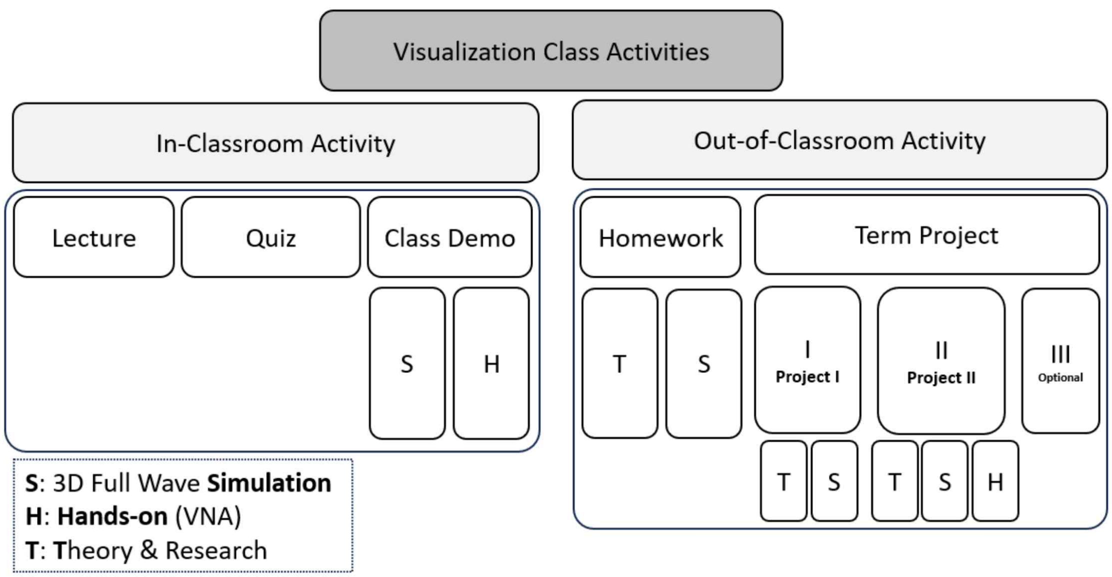
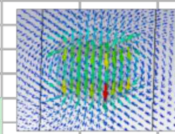
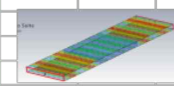


Figure 3. Example Class Activity Map with in-classroom and out-classroom activities of LeTourneau University

Fig. 4 shows an example and excerpt of the module navigation map for analysis of lecture and homework. Lecture sequence and connected homework set are reviewed to restructure and assign the time slots for embedding hands-on materials.

ECE 343 Spring 2023					
CST	AWR	Smith Chart Tool	Additional	Possible Hands On	Visualization Capture
HW 1	1	Euler's Identity			
	2	Phasor notation			
	3	Inductor Voltage			
	4	Capacitor Current	Discontinity - no flow of physical electron, Displacement current		
	5	Capacitor: Electric Field		CST Installation	
	6	Capacitor: Electric Flux		Capacitor Example Demo	
HW 2	1	Telegrapher's equation			
	2	Wave Equation			
	3	Wave Equation Derivivation		EM wave propagation demo	

Note: The entire content is omitted for space constraints.

Figure 4. Table generation to embed hands-on materials (U.S. Air Force Academy Course)

As an example of applying both analysis of module and sequence and class activity map, authors can effectively consider and design modulization of activities along with appropriate visualization and hands-on. In this layout, instructors can more easily select and decide modules for visualization and hands-on modules. Rather than changing and designing entire structure and contents, modular approach gives more flexibility reflecting on uniqueness or special conditions of class.

Visualization Tools

1) 3D full wave simulator

Traditionally, MATLAB and other tools are convenient to display the EM waves and visualize them; however, practically, there are not many practicing engineers who use MATLAB to visualize and analyze the time-varying EM fields with complicated objects and targets. The authors considered 1) the industry driven needs for students' preparation: 3D full wave simulations are more effective and practical for students' learning and being prepared to the industrial or research job market as they use 3D full wave simulators. 2) better visualization 3) affordable or open source. In the class, the authors, as course instructors as well, introduced a 3D full wave simulator with educational or student edition from the software company website as anyone can register and obtain the downloadable installer and its license. Instructors designed the course module along with the simulator, and students received the assignment to experience it. Since the class time is limited, the modules are designed for students to run a prebuilt module by the instructor or software company for their visualizing EM fields instead of mastering the tool itself. With the prebuilt module, students save the time and easily adjust the parameters for their analysis. The following topics are well connected to the simulation examples:

1. Electrostatics: Sphere, Sphere with layer, Two Sphere conditions with different polarities
2. Boundary Condition, Method of Image: Simulation Setup, Symmetric boundary conditions
3. Antenna: Time Varying Field Representation, Method of Image with monopole antenna
4. Wave propagation in the space, with slab, incident wave excitation, boundary condition

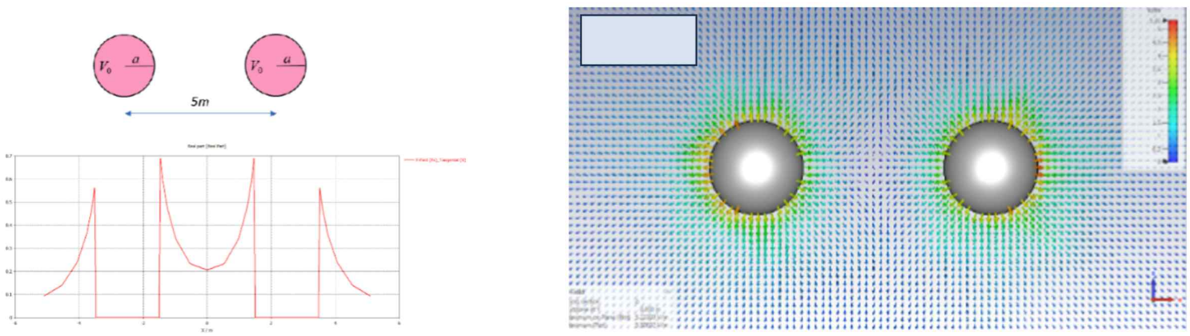


Figure 4. Full wave EM simulator example: Theory, Simulation, and Visualization

2) AWR Microwave Office

AWR stands for "Applied Wave Research," which is the company that originally developed the software before being acquired by Cadence. AWR aims for RF / Microwave Design & Analysis to provides from circuit level to system level simulation including convenient tools to represent Impedance Matching, Smith Chart, S-parameter, Filter Design, etc. Fig. 5 and Fig. 6 show the examples using AWR to visualize the relevant concepts and in-class practice.

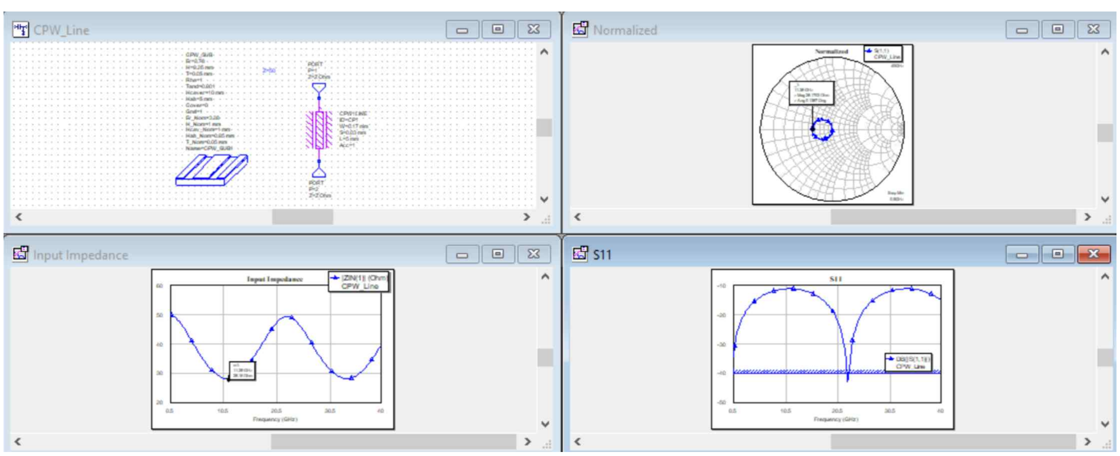


Figure 5. AWR examples: Smith Chart, S-parameter

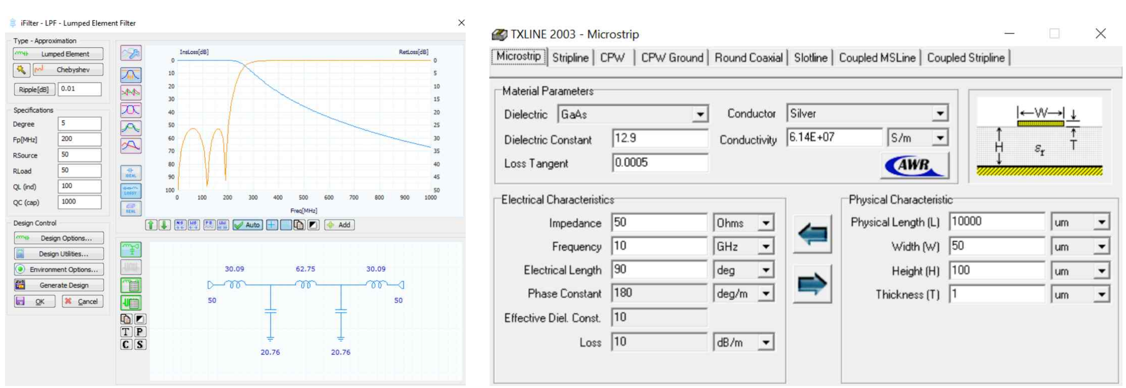


Figure 6. AWR additional tools: iFilter for distributed circuit, S-parameter, TXline for distributed element and impedance matching

3) Hands-on Measurement

The instructors introduced a portable and affordable VNA (Vector Network Analyzer) into the class along with the S-parameter concept. The lecture covers the distributed element basics with why the EM analysis is more critical as the operating frequency goes high, and with the antenna design and its measurement. Students need to fabricate the dipole antenna which is introduced when the method of image was explained along with the concept of monopole antenna and its half size. Students used the full wave simulator to run the result of dipole and monopole antenna at the specific target frequency such as 1 GHz. They can use a simple connector and wires to build the antenna. After building it, students use VNA to measure the s-parameter to compare the results. Fig. 7 shows the hands-on project that students learn theory, simulation, building, and measurement in Antenna Project.

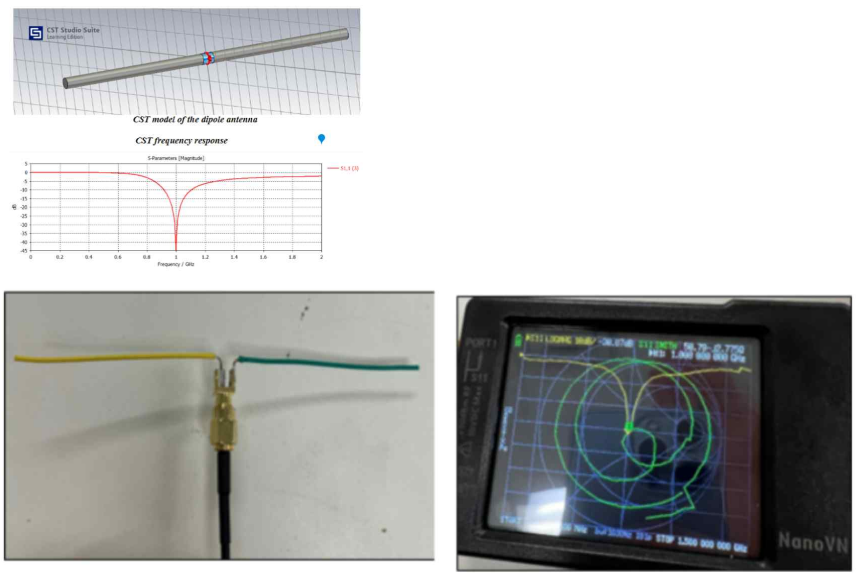


Figure 7. Antenna Project Example: Simulation, Built, Measurement using VNA

Assessment

Survey For Learning Experience

Most of the students were positive to experience and learn a full wave simulation tool and hands-on experience; however, at the same time, limited time and resources due to the class setup without separate lab were still making hard for some students and their learning with the feedback to have more resources to learn about the tools.

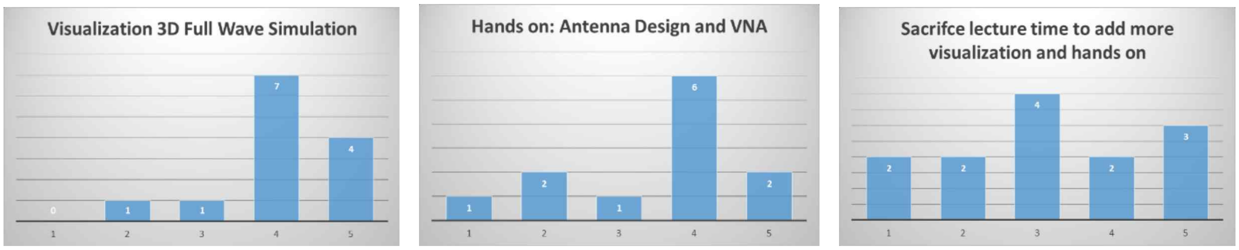


Figure 8. Survey Results: Visualization, Hands-On, Sacrifice lecture to earn more time

The following is the collection of student comments with the survey question about the most helpful learning experiences or tools except the normal lectures such as explaining the concepts and solving the examples in the class. Table IV shows the collective summary of student open responses about their learning experiences for sharing their most helpful class activity and any feedback with asking challenges or thoughts to improve their learning experience. Table IV lists the categories which may be combined terminology or independent term keeping students' wording. As an example, Term Project I includes multiple components including VNA, Simulation, Build, and Test of Antenna including the report. Instead, there are a few independent terms such as 3D full wave simulation (CST Studio Suite Learning Edition), VNA, etc.

Table IV. Collective feedback: 1) most helpful activity, 2) challenges, and 3) suggestions

1) Most Helpful Activity
• 3D Full Wave Simulation
"Seeing the visuals in CST helps a lot The visualizations on the different fields in CST helped understand the core concepts." "…helpful in explaining the Method of Image get a better understanding of what they look like in the real world…" "…but overtime it became very useful as a visual aid"
• Portable Vector Network Analyzer
"… hands-on application with the nanoVNA" "I would strongly agree that the work with the nanoVNA helped me understand the concept of S parameters and related Electromagnetic Fields and Wave content"
• Term Project II
"… Term Project II. I enjoyed using what I learned in class like the method of image to design a monopole antenna…"
2) Challenges
"Technological troubles – Installation, License" "…having to take the time to learn difficult time with the problems in homework and tests." "… hard to navigate the software as someone who is new at using this software and the tutorials help with learning how to get the indicated result." "… struggled for awhile in the beginning of the semester to understand how to use CST …"
3) Suggestions
"… almost be better to add a lab section, which could be dedicated to

visualizations and simulations" "… have liked to go more in depth with CST to be able to use it for a more practical application" "More written instructions on how to operate CST and a well written example for each concept" "… provide more instructions with the CST assignments" "I don't feel like the class really has time for a tutorial of CST during class, but perhaps if you made a recording for CST that could be helpful" "… more visuals on the time-varying fields …"

Some students express concerns and difficulties, resulting in low scores for their learning experience. The follow-up survey revealed that issues such as time consumption, the need for more detailed instructions, and sometimes personal preferences contribute to these challenges. The first two results in Fig. 8 indicate an above-average rating for students' positivity towards using visualization tools. However, the third figure shows a more varied outcome, suggesting the need for careful consideration and additional resources. Time constraints remain a challenge for senior students, as they have numerous other commitments, potentially limiting their ability to fully engage with the tools and leading to rushed experiences. Regarding the significance of course continuity in curriculum, authors investigated how curriculum continuity increases the learning effectivity. The survey showed that junior students rated higher in two specific questions 1) meaningful connection between preliminary math and physics courses and the Electromagnetics course, rated 4/5, and 2) easiness to apply, rated 4/5, compared to scores of seniors with 3.4/5 and 3.3/5 respectively. This may directly and indirectly support the importance of course continuity and the placement of connected courses without a gap of two years or more between math/physics courses and Electromagnetics, increasing students' learning effectiveness. Authors also found that students expressed differences in similar topics in other math courses compared to the ones used in the Electromagnetics course, particularly in the description of coordinate system notations, leading to more confusion. Under these students' difficulties, both junior and senior student groups mentioned that reviews are helpful and necessary. However, high-achieving students in both junior and senior years who received A grades noted a rating of 4/5 for the same question about the helpfulness of reviews, while others marked 5/5, indicating room for minimizing reviews to cover the course major topics and activities more thoroughly.

Conclusion

The authors conclude that visualization using the tools introduced works well, particularly for some students who show more interest in specific tools and hands-on. This visualization should be applied efficiently and effectively to reflect the constraints of the class environment. Embedding the visualization techniques adds more diverse approaches to enhance students' learning. With careful module selection and even material drops to optimize the class modules and add visualization and hands-on activities, the class can be more balanced as it maximizes students' learning. There are some drawbacks as the authors identified the class barriers, and there is still room to make the class smoother and more organized with more prepared resources to reduce the time and contents challenges in students' learning. Moreover, a single course like

Electromagnetics can be redesigned and aligned along with the entire curriculum sequence. Not only class placement in the semester, but communication and collaboration among different instructors to cover the continuous courses would be required and would be very helpful to choose the adequate modules with priority. Last, the authors suggest that the class itself is not only delivering knowledge and technique but also building relationships and inspiring the class. There are many areas to improve and make it refined along with this framework to add visualization and active for enhancing students' learning experiences. As a recommendation to other instructors, the authors could see the differences between universities since the class setup and students are different in context. However, considering the outcomes of the target course, and approach to include theory, simulation, measurement would be critical for students' in-class learning and future careers reflecting industry's demand. Each instructor may generate their own modularized course design charts and consider visualization tools to combine those.

Acknowledgement

This research and collaboration is supported by U.S. Air Force Research Lab Summer Faculty Fellowship Program named as USAFA: Pedagogy Research for Education in Electrical and Computer Engineering.

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