

Brief Report

Designing Engineering Courses with Embedded Virtual and Real Experimentations

Ashanthi Maxworth 

Department of Engineering, University of Southern Maine, Gorham, ME 04038, USA;
ashanthi.maxworth@maine.edu

Abstract: Engineering requires solid mathematical knowledge in addition to hands-on experience. At the same time, finding the right balance between mathematics and applications is challenging. This paper presents the implementation of virtual and real experiments in three math-heavy engineering courses at the University of Southern Maine. These courses were Communications Engineering, Antennas, and Plasma Engineering. Furthermore, the virtual experiments implemented were MATLAB R2022b simulations, HFSS simulations, and videos. The real experimentation included antenna building, a software-defined radio project, a 3D printing project, and a case study analysis. These virtual and real experiments were distributed between the aforementioned three courses. Based on student feedback, having these virtual and real experiments aided their learning process and students enjoyed having hardware experiments embedded in a course.

Keywords: virtual experimentation; real experimentation; projects; simulations; problem-based learning

1. Introduction

Background

Engineering is an applied field based on mathematics and physical sciences. Hence, it is often challenging to find the right balance between hands-on experience and theoretical knowledge [1]. Although every engineering course is based on one or more branches of mathematics and physics, this challenge is apparent in courses which are heavily based on mathematics and physics such as electromagnetic fields [2–4]. Finding the balance between theory and practice has been a topic of discussion within the engineering community for many years [2–4].

Recent research suggests having hands-on experimentation improves the quality of learning in engineering [5]. These hands-on experiences can be embedded in the forms of virtual experimentations or simulations where the students can experiment with different conditions. Research suggests that undergraduate engineering students prefer virtual experimentation over real experimentation given that the risks associated with making a mistake are literally non-existent [6–11]. Based on the same reason, even the engineers in the industry perform simulations as the first step of their design process to avoid the risks of failures and associated costs of real experimentation [12]. Virtual experimentation is also appealing given that it can be easily implemented into instructor-led classroom activities [11], where the instructor can teach a concept and perform a simulation activity with the students according to the gradual release technique [13].

Real experimentation and project-based learning are two important aspects of engineering education that give students more hands-on experience [14–16]. Research shows having hands-on experimentation in addition to theory enhances student learning and makes students more interested in their future careers. In addition, having these hands-on experiences in a more project-based setting allows students to work in groups simulating a real-world scenario [16]. Having real experimentation within a project-based setting allows



Citation: Maxworth, A. Designing Engineering Courses with Embedded Virtual and Real Experimentations. *Educ. Sci.* **2023**, *13*, 610. <https://doi.org/10.3390/educsci13060610>

Academic Editors: Ji Han, Pingfei Jiang and Liuqing Chen

Received: 3 May 2023
Revised: 10 June 2023
Accepted: 13 June 2023
Published: 15 June 2023



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students to develop soft skills such as communication and team building while gaining hands-on experience.

Problem-based learning [17,18] and case study analysis [19–21] are two other ways to expose students to real-world applications in a traditional lecture environment. These two techniques could be implemented in any course regardless of the discipline since they do not need additional software or hardware. Research on engineering education shows that these two techniques are as powerful as real and virtual experimentation in terms of exposing students to real world scenarios [19–21]. In addition, having multiple of these effective teaching techniques enhances the student learning experience the most [22].

This paper presents the application of the innovative teaching pedagogies discussed above in three engineering courses taught at the University of Southern Maine. The engineering courses discussed in this work are ELE 483: Communications Engineering, ELE 452: Antennas, and EGN 321: Plasma Engineering. All these courses are taught by the author (hereafter referred to as I) of this paper. Before moving into the implementation, here is an introduction to the student body at the University of Southern Maine's engineering department [23].

The University of Southern Maine is primarily an undergraduate teaching institution. The engineering department is composed of the electrical and mechanical engineering disciplines. The faculty and the students of these two disciplines are within the same department under one Department Chair. Given the co-existence of two disciplines within the same department, most engineering undergraduates major in one field while minoring in the other, increasing their potential for employment. Additionally, engineering students can take technical electives from either discipline to fulfill their graduation requirements. In addition, there is almost a 50%-50% balance between traditional and non-traditional students within every department in the university. The courses discussed in this paper are junior- and senior-level courses. Moreover, all the junior and senior undergraduate students in the engineering department are commuter students.

As a faculty member teaching math-heavy engineering courses, i.e., electromagnetic fields, communications engineering, and plasma engineering, it is always challenging to find the right balance between theory and application within a 16-week semester. Given the complicated mathematics and physics concepts, it is important to test the student right after teaching a concept to make sure they learnt the concept well before moving on to the next. Therefore, I am a strong believer of the teach-then-test concept.

As an educator, my goal was to make sure every student gets the most out of a course. In the pedagogical innovations presented in this work, the hands-on experiments are embedded in the lecture course itself, such that right after the students learn a theoretical concept, they perform either a virtual or a real experiment. This technique is developed based on two grounding principles:

1. Engineering students need to have a solid understanding of the mathematical and physical concepts behind the applications. This is important for engineers who want to design new systems. Skipping important mathematics and physics concepts makes the students vulnerable when they are presented with unfamiliar real-world scenarios.
2. The knowledge must be complete with either virtual or real experimentation. Students have diverse learning styles; hence, the teaching needs to be diverse as well.

The following sections discuss the implementation of the engineering courses, the student feedback, and future improvements.

2. Implementation

The Engineering Courses

The first implementation of this diverse set of teaching techniques was in ELE 483: Communications Engineering in the spring of 2021. The second offering of this course was in the spring of 2023. During the first offering, the course was offered in the hybrid format and during the second offering, it was offered in person. However, given that the

course is highly mathematical, the lectures were recorded and uploaded into the learning management system within the same day.

The ELE 483: Communications Engineering course starts with an introduction to a random variable, and random processes followed by a discussion of the expected value, correlation, and covariance. To dive into these concepts, students need a thorough understanding of probability and statistics. Next, the course continues onto power spectral density, noise, in-phase, and quadrature components, requiring a solid understanding of signal processing concepts such as the Fourier transform and linear filtering. Toward the middle of the semester, the course moves onto continuous wave modulation techniques, amplitude modulation, angle modulation, and frequency modulation followed by coherent detection, geometric representation of signals, and maximum likelihood decoding. All these topics are based on signal processing concepts. After the 10th week of the semester, the course moves onto digital communications starting from the Shannon–Nyquist sampling theorem, quantizing, encoding, and matched-filter designing followed by the digital modulation techniques of amplitude shift-keying, frequency shift keying, and phase shift keying. All these topics are based on all branches of mathematics and signal processing. To make sure students do not become lost in the numbers and math, it was important to introduce hands-on experiments in this course. Therefore, this course included MATLAB™ [24] simulations and hands-on experiments with Rhode & Schwartz FPC Z10 RF teaching kits and software-defined radios. Table 1, column 2, lists the MATLAB simulations and the real-experiments conducted. A sample MATLAB simulation exercise sheet is given in Appendix A.

The second course, ELE 452: Antennas, was offered first in the spring of 2022 as a technical elective. The ELE 452: Antennas course started with a review of electromagnetic fields, followed by the analytical derivation of electric and magnetic fields for the Hertzian dipole, an electrically small dipole, and the introduction of antenna parameters such as gain, directivity, bandwidth, and impedance. During this derivation, the concepts of near field and far field were introduced as well, together with their capacitive, inductive, and resistive behavior. Under this course, we discussed ten different types of antennas, starting with linear-wire type quarter-wave monopole, half-wave dipole, and loop, followed by antenna arrays and a discussion of the self and mutual impedance of antenna configurations. After that, we talked about the techniques of impedance matching, such as quarter-wave stub matching and the use of the Smith charts. Towards the middle of the semester, the course continued to broadband antennas such as bi-conical antenna and ruffle-skirt antennas, then to traveling wave antennas, such as helical antennas, and then to frequency-independent antennas. Towards the end of the semester, the course moved onto the topics of log-periodic antennas, and aperture antennas such as the horn antenna and the dish antennas. The course was concluded by discussing the microstrip patch antenna.

In the Antennas course, students simulated ten different antennas on HFSS™ [25] in class. When it comes to antennas, the mathematical derivations can be quite cumbersome. Furthermore, if a student knows how to carry out the derivations of electromagnetic fields for one type of antenna, that knowledge is directly transferable to the other types of antennas. The simulations and the real experiments are listed in column 3 of Table 1. Students received step-by-step guidance for HFSS simulations. In addition to these real and virtual experiments, the students completed two case studies: (1) a case study on large antenna arrays, (2) a case study on novel antenna types for biomedical applications, and (3) a case study on smart antennas. Students prepared video presentations for the first two cases and for the third case study, they prepared an infographic. Appendix B shows the case study analysis assignment sheet and the grading rubric.

ELE 321: Plasma Engineering was offered for the first time as a technical elective in the fall of 2022. This course received a higher education curriculum development grant from the Maine Space Grants Consortium. One requirement of this award was to incorporate material from the National Aeronautics and Space Administration (NASA). Therefore, the course had an emphasis on space plasmas which was ideal given that

99.9% of space material is in a plasma state. The course started with an introduction to the general properties of plasmas and natural plasmas. The discussion soon moved on to single particle motion under different electric and magnetic field configurations. After discussing all the electric and magnetic field conditions and the particle behavior under each situation, the course moved on to plasma kinetic theory to analyze plasma particle populations. Towards the middle of the semester, the course topics were plasma equilibrium, macroscopic transport equations, plasma conductivity, and diffusion, followed by magnetohydrodynamics. Towards the end of the semester, we discussed the topics of the pinch effect and magnetohydrodynamic waves, and concluded the course with plasma waves and wave–particle interactions. The students who were enrolled in this course had no prior knowledge of plasma physics, which made the course extra challenging.

In addition to hands-on MATLAB simulations, the plasma engineering course included three guided tours of NASA facilities. The first one was a tour of the power and propulsion lab of the Johnsons Space Center [26], the second was a guided tour of the NASA Jet Propulsion Laboratory [27] and the third was a general tour of the Johnson Space Center. These tours were scheduled outside of class time given the availability of the NASA center. Moreover, during the course, the videos and animations from the NASA Conceptual Image Laboratory [28] and the NASA Visualization Explorer [29] were used frequently to demonstrate advanced plasma concepts. There was also a guest speaker to demonstrate research in this field.

Table 1. The virtual and real experiments conducted in communications engineering, antennas and plasma engineering.

Experimentation	ELE 483: Communications Engineering	ELE 452: Antennas	EGN 321: Plasma Engineering
MATLAB or HFSS simulations.	Random number generation using MATLAB	Quarter wave monopole in HFSS [30]	MATLAB simulation for electrons and ions with only a perpendicular velocity (circular motion)
	Fourier transform in MATLAB	Meshing [31]	Single particle motion with constant parallel and perpendicular velocities (helical motion)
	Linear time invariant filters	Half-wave dipole [32]	$\mathbf{E} \times \mathbf{B}$ drift
	Amplitude modulation on MATLAB	Antenna near field and far field [33]	Gradient drift of charged particles
	Envelop detection	Loop antenna simulation [34]	Curvature drift
	Frequency modulation	Antenna arrays [35]	Plasma particle populations based on the Maxwell–Boltzmann distribution
	Sampling, quantizing, and encoding in MATLAB	Bi-conical antenna [36]	Magnetic bottles
	Amplitude shift keying in MATLAB Simulink	Helical antenna [37]	Pinch effect and plasma confinement based on particle pressure and magnetic pressure.
	Frequency shift keying	Horn antenna [38]	Dispersion relation of plasma waves
	Phase shift keying		
Coherent detection	Microstrip patch antenna [39]	Refractive index surfaces of plasma waves	
Maximum likelihood decoding in MATLAB			

Table 1. Cont.

Experimentation	ELE 483: Communications Engineering	ELE 452: Antennas	EGN 321: Plasma Engineering
Projects and real experiments	Building an RF transmitter and receiver using the Rhode & Schwartz FPC Z10 RF teaching kits.	Assembling a Yagi antenna and observing the signal spectrum using a spectrum analyzer (group project of three students)	Designing an ionosonde (frequency ramps of 1.6 MHz–12 MHz) tracker using software-defined radios.
	Observing signal power and noise using software-defined radios.	Designing and printing a microstrip patch antenna (group project of three students)	3D printing a retarding potential analyzer to separate different types of ions.

In addition, all these three courses had two in-class examinations in the 6th and 10th weeks in addition to a final examination. All these courses had homework assignments assigned bi-weekly and four to five quizzes spread throughout the semester. These traditional assignments helped solidify their quantitative reasoning skills and all the exams had design questions where they had to select parameters and plan the design process.

3. Student Feedback

Students provided end-of-semester feedback through the faculty course questionnaires. Students could provide quantitative and qualitative feedback. This section presents the feedback received for the real and virtual experimentations.

3.1. ELE 483: Communications Engineering

Student feedback mentioned that the MATLAB exercises helped them learn the concepts. They also suggested having a lab section with hardware experiments. As mentioned above, most of the students joined the class online given the pandemic. Therefore, it was not feasible to implement a hardware lab. However, since the course is offered in person in the spring of 2023, there is a hardware lab section. The details are given in the current and future improvement section.

3.2. ELE 452: Antennas

In this course, the main comments were that the course was great and very informative, and the students appreciated the conceptual simulation-based method over the math-heavy approach. The students also appreciated the training they received in HFSS software which will aid them in their employment.

3.3. EGN 321: Plasma Engineering

This course contained a variety of virtual and real experiments. Therefore, as the instructor, it was important for me to extract the most effective experiments. Given that this course received a grant from the Maine Space Grants Consortium (acknowledged in this paper), for grant purposes, students had to answer a few custom questions specific to the virtual and real experimentations. Those questions and feedback are given below. Out of 21 students, 14 of them provided feedback.

1. Agree or disagree on a 1–5 scale: the in-class MATLAB simulations helped me visualize mathematical concepts. Results: nine students strongly agreed that the in-class MATLAB simulations helped them visualize the mathematical concepts, four students agreed, and one student disagreed with this statement. Figure 1 shows these results graphically.

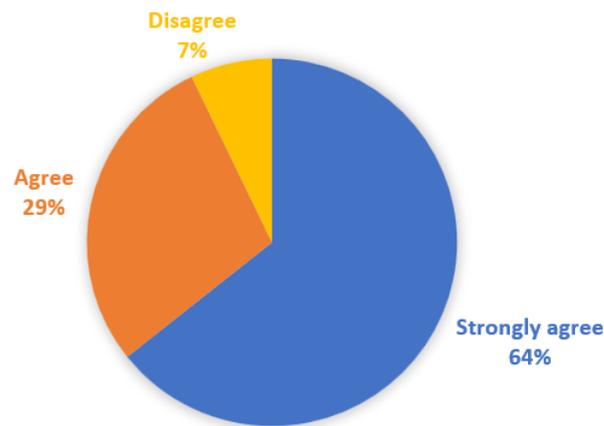


Figure 1. Graphical representation of student feedback on the effectiveness of MATLAB examples on visualizing mathematical concepts.

2. Agree or disagree on a 1–5 scale: the in-class simulations helped me learn MATLAB or gave me more experience in MATLAB. Results: 10 students strongly agreed with this statement, while one student agreed, one student neither agreed nor disagreed and two students disagreed. A graphical view is shown in Figure 2.

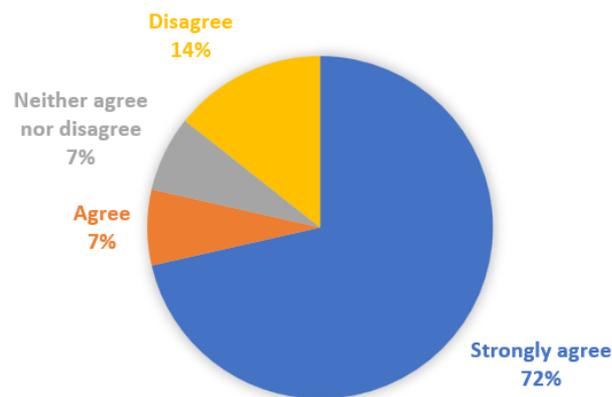


Figure 2. Graphical representation of student feedback on the effectiveness of the virtual experiments on learning MATLAB.

3. Agree or disagree on a 1–5 scale: the NASA videos shown in class tied in-class knowledge to the broad picture of space plasma physics. Results: nine students strongly agreed with this statement while five students agreed. These results are shown graphically in Figure 3.

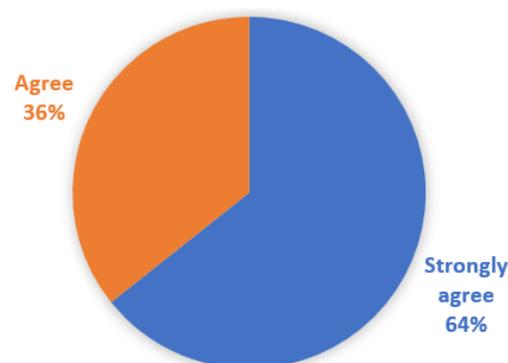


Figure 3. Graphical representation of student feedback on the effectiveness of NASA videos in tying in-class concepts to the broad picture of plasma physics.

4. Agree or disagree on a 1–5 scale: the projects gave me a chance to try out software-defined radios and 3D printing. Results: 11 students strongly agreed with this statement, four students agreed and one student neither agreed nor disagreed. These results are shown graphically in Figure 4.

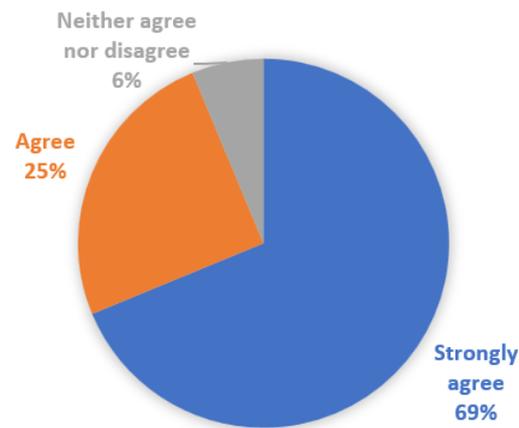


Figure 4. Graphical representation of student feedback on the effectiveness of the projects on practicing 3D printing.

5. Agree or disagree on a scale of 1–5: the tours of NASA centers showed me how the in-class concepts are being used in the real world. Results: six students strongly agreed with this statement, three students agreed and two students neither agreed nor disagreed. Figure 5 shows these results graphically.

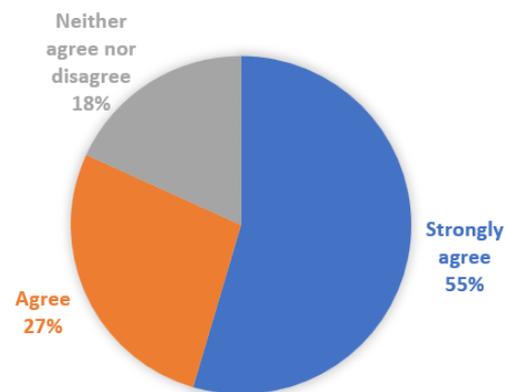


Figure 5. Graphical representation of student feedback on the effectiveness of the NASA virtual tours in exposing them to the real-world scenarios.

Qualitative feedback received regarding the course indicated the following:

1. “The Course was excellent and very well taught. I liked using MATLAB and it helped me better understand what was going on. The projects were also a good visual and fun to do”.
2. “This course offers a great insight into plasma and how it applies to communications and space ion engines”.

Based on the quantitative and qualitative feedback received, all the virtual and real experiments were effective. The quantitative feedback indicates that the students enjoyed real experimentation in a lecture course.

4. Discussion

The course ELE 483: Communications Engineering was offered for the second time in the spring of 2023. During this time, there were hands-on experiments that involved

RF teaching kits and software-defined radios. The student feedback was overall positive. As the instructor, I am thinking of introducing a field trip and a case study analysis for this course to demonstrate to students how all these concepts fit into the big picture of communications engineering. Although the current active learning techniques help students to comprehend the mathematics of the course, some students have a hard time understanding where each concept fits in the industry. Communications engineering is a vast field with multiple specializations within it, for example, radio frequency receiver design, network design and planning, antenna design and information theory and coding. During the course, each of these sub-areas was introduced. Having a case study analysis will help students in understanding the extent of communications engineering and to identify their field of interest. Introducing a field visit will be a novel experience for the students where they will be able to see the theories in action and interact with the engineers in the field.

For the ELE 452: Antennas course, the worksheets I prepared were published online as an open educational resource and have been downloaded worldwide. By the time of writing, they have nearly 700 downloads around the world. One student who graduated two years ago, now working in his own start-up antenna installation company, sent me an email thanking me for preparing those worksheets. He mentioned that he was searching how to model a helical antenna on HFSS and found the worksheet on helical antennas within the top three search results. Knowing that the work I put in as the instructor of the course is useful for people worldwide, including my own students, is a wonderful feeling for an academic.

Another important outcome of the antennas course was a conference publication made by an undergraduate student [40]. This is an important achievement due to two reasons: 1. It was published by an undergraduate while taking the course ELE 452: Antennas under my supervision. 2. That conference paper [40] shows the importance of math and analytical solutions, and the fact that we cannot rely solely on software. In that paper, the student modeled a crossed-dipole antenna using HFSS and another industrial-level antenna simulation software called FEKOTM [41]. Although both HFSS and FEKO produced accurate solutions when the crossed dipoles were one wavelength long, they both produced incorrect results when the dipole lengths were reduced to half of a wavelength. Implementing the antenna radiation pattern analytically on MATLAB produced the correct radiation patterns for both antenna lengths. The reason for the HFSS and FEKO discrepancy is still not known. However, the most important take-away from this was that every RF engineer should know the analytics and how to interpret the results. Relying solely on a numerical software can damage the credibility of the engineer and may be dangerous.

As for the ELE 452: Antennas course, in the next offering I do not plan to change any of the course content. One interesting addition would be to take the students on a field trip to the MIT Haystack facility [42] where they have a giant antenna. This course already has virtual experimentation, real experimentation and three case study analyses, and the only missing activity is a field trip. Once the field trip is introduced, the course would be complete.

The EGN 321: Plasma Engineering course already has a diverse set of teaching techniques, including virtual experimentation, real experimentation, NASA videos, NASA facility tours and guest speakers. Contrary to the findings in the literature, the informal verbal feedback from the students suggested that they enjoyed the projects (real experiments) more than the virtual experiments. During the previous offering of the course, I did not specifically ask them which learning technique was the most effective; therefore, I do not have solid data to prove this statement. Yet, I think this point is worth investigating in the next offering of the course. To balance the composition of virtual and real experimentation of this course in the next offering, there will be three mini projects instead of two.

My suggestion for educators who are teaching similar courses, is to integrate a variety of teaching and assessment techniques in your courses. This integration needs to be carried out gradually with few variations at a time, for example, by introducing simulations into

traditional lectures. Moreover, gradually as you, the instructor, becomes more comfortable with the new pedagogy, you may introduce other new methods while eliminating the ones which were not effective in your course. By including virtual and real experimentation, videos, tours, case studies and projects as you see fit, your courses will facilitate learning in students with different learning styles. At the same time, embedding new pedagogy keeps the teaching process interesting for the instructor.

The practical implications of this hybrid pedagogical approach are: 1. students gain proficiency in new software that they can immediately apply in their jobs, 2. students gain the ability to use state of the art equipment, reducing their time to adapt in a new job, and 3: students gain the ability to research and find solutions to a novel or existing problem themselves. In addition, students gain soft skills such as working in a group and communications skills. The theoretical implication is the contribution to the engineering education body of knowledge. Unless we test multiple pedagogies, it is hard to determine the most effective method for each group of students as well as each individual student.

The human brain stores different types of learning (visual, auditory, kinesthetic, etc.) at different but interconnected regions [43]. As noted in [43], considering multiple teaching techniques which are proven to be effective helps students consolidate their knowledge by building strong neuronal interconnections, and recalling those whenever necessary. By incorporating novel pedagogy, we not only fulfill our responsibility of teaching the courses, but also leading the path of lifelong learning for our students.

5. Conclusions

At the engineering department of the University of Southern Maine, electrical and mechanical engineering disciplines coexist. Hence, most the students either double major in those to fields or major in one, while taking a minor in the other, making their education multidisciplinary. This paper discusses three courses—ELE 483: Communications engineering, ELE 452: Antennas and EGN 321: Plasma engineering. In all three of these courses, a variety of active learning techniques are implemented, including virtual experimentations, real experimentations/projects, and case study analysis. The real experimentations/simulations were conducted either on MATLAB or on HFSS, while the projects included working with software-defined radios or 3D printers. The case studies were from real-world current applications to show students the vastness of the applications. From the qualitative and quantitative feedback received from the students, the virtual experiments helped them visualize mathematical concepts while giving them a chance to learn a new software program. In addition, being exposed to real-world scenarios through tours and videos broadened their knowledge while connecting in-class learning to the big picture.

Funding: This work is supported by the Maine Space Grants Consortium's Higher Education Curriculum Development Award #SG-22-24 to Dr. Ashanthi Maxworth.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Consent was waived since the paper does not carry any personally identifiable information.

Data Availability Statement: Readers interested in obtaining anonymous student feedback are requested to contact the author of this work through ashanthi.maxworth@maine.edu.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A. MATLAB Exercise from ELE 483: Communications Engineering

In this exercise you will

1. Generate a message signal and a carrier signal
2. Amplitude modulate the message signal
3. Add Gaussian random noise to the modulated signal
4. Generate the power spectral density of the modulated signal plus noise

Steps:

1. First, let's generate the time axis as follows,

$$F_s = 30,000;$$

$$t = 0 : 1/F_s : 1-1/F_s;$$

2. Create a message signal with 1 kHz, and a carrier signal with 10 kHz. Let the amplitude of the carrier be 3 V. Plot the modulated signal, change the modulation index and observed the ideal, over and under modulated conditions.
3. Using the inbuilt MATLAB command `randn`, generate zero mean unit variance Gaussian random noise. And add to the modulated signal.
4. Then let's plot the power spectral density of the modulated signal (y) plus noise. A portion of the code is given below.

```
N = length(y);
ydft = fftshift(fft(y));
psdy = (1/(Fs * N)) * abs(ydft).^2;
freq = -Fs/2 + Fs/length(y) : Fs/length(y) : Fs/2;
plot(freq, 10 * log10(psdy))
grid on
title('Power Spectrum Using FFT')
xlabel('Frequency (Hz)')
ylabel('Power/Frequency (dB/Hz)')
```

Appendix B. Antenna Array Case-Study from ELE 452: Antennas

Goal: There are large antenna arrays in the world built for various purposes. Your goal is to study one such large antenna array and elaborate on the following.

Skim the webpages of the following antenna arrays and pick one array system to study deeper.

1. Very large array: <https://public.nrao.edu/telescopes/vla/> date accessed: 5 February 2022
2. HAARP: <https://haarp.gi.alaska.edu/>, date accessed: 5 February 2022
3. Square Kilometer Array: <https://www.skatelescope.org/>, date accessed: 5 February 2022

Create a 5–7 min video elaborating on the following;

- a. What type of antennas is being used in the array (dipoles, dish, parabolic, etc.)?
- b. How many arrays are in the array?
- c. Are all antennas identical in shape, gain, etc.?
- d. What is the array configuration i.e., linear, planer, circular, a hybrid?
- e. How much are the minimum and maximum input power?
- f. Maximum output power?
- g. Are all antennas being fed by the same source or is there a phase difference between each input signal?
- h. Is it a phased array?
- i. Note: In antenna theory, a phased array usually means an electronically scanned array, a computer-controlled array of antennas that creates a beam of radio waves that can be electronically steered to point in different directions without moving the antennas—Wikipedia.
- j. What are the different beam patterns created by the antenna array?
- k. What are the maximum gain, directivity, etc.?
- l. For what purposes your chosen antenna array is being used?
- m. What are the unique capabilities of your chosen antenna array?

You may use any video recording software. Feel free to use images and diagrams as needed. Make sure that your video has audio embedded into it.

Grading criterion:

1. Depth of research 15%
2. Answering all questions asked within the presentation 25%
3. Quality of the visual presentation 30%
4. Quality of verbal communications 30%

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