2006-98: A MODULAR PEDAGOGY FOR TEACHING UNDERGRADUATE ELECTROMAGNETIC FIELD THEORY

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A Modular Approach for Teaching Applied Undergraduate Electromagnetic Field Theory

Abstract

Electrical engineering and physics students are required to take a full-year electromagnetic field theory (E&M) sequence at the University of St. Thomas (UST). The E&M sequence is jointly taught by both departments. This enables students the opportunity of learning E&M from the perspective of both disciplines. A traditional lecture format was originally used by both departments for teaching this sequence. Unfortunately E&M taught with a lecture format fails to develop applied E&M skills. Since the mission of the UST School of Engineering (SOE) is to "… provide an **applied** … learning experience …" and since there were no labs associated with the original approach, this presented an 'applied' problem. In addition to this, a majority of the UST engineering and physics graduates begin their professional job careers immediately after graduating. Of the remaining graduates that do pursue an advanced degree, few continue with their study of E&M. Since a substantial amount of time is dedicated to E&M and since undergraduate credit hours are precious, the challenge was to develop an E&M pedagogy that imparted an applied E&M learning experience without significantly increasing the number of contact hours. An eighteen month investigation was conducted to address this challenge. Based on the results of this study a modular pedagogy was developed that satisfied the 'applied' mission objectives without significantly increasing the number of contact hours. The new modular pedagogy combines state-of-the art laboratory metrology and analysis practices with enough theory to enable the students to understand the significance of their measurements. About three weeks are required to complete each module. Based on inputs from multiple professional sources, applied modules were developed for the following topics: Mathematical foundation of field theory, E&M dynamics, transmission lines, antennas, and the use of finite element software such as ANSYS® and FEMLAB® for solving practical E&M problems. Preliminary results from using this pedagogy will be presented along with implementation attractors and detractors.

Introduction

The motivation for offering an integrated, inter-departmental applied undergraduate physics-engineering curriculum at UST is shaped by the goal of providing graduates with a practical skill set that is attractive and useful to prospective employers. Experience has shown that excellence in mastering E&M theory does not directly translate into competence with E&M metrology or laboratory practices. Since a majority of the UST engineering and physics students that graduate go directly into the work force, these observations motivate several questions. For example, when undergraduates enter the work force, what constitutes an optimal technical skill set (to the extent that such an 'optimal skill set' exists)? For the SOE, inputs from many sources (such as the Industrial Advisory Board (IAB), other corporations, general faculty, other schools, and so forth) are used to quantify the characteristics of this ‘skill set’. Since E&M is considered to be foundationally important by all UST share holders, and given the constraint of only two semesters for study, much attention has been given to selecting the appropriate E&M topics that are covered. The selection of topics is also tightly coupled with discussions on how applied undergraduate E&M should be taught. In addition, the set of E&M skills that will adequately prepare our undergraduates for the work force has been closely scrutinized. The need to address these questions provided the framework for a recently concluded study titled, “Engineering Electromagnetic Fields and Waves.” This study was funded through a Teaching Enhancement Grant which supports research on pedagogy. The results of the study are summarized in this paper along with the implementation of the pedagogy. Some of the preliminary outcomes are also presented.

Recently there have been several excellent studies supporting the need to improve the E&M teaching pedagogy at all levels[1, 2]. As pointed out in these references, the traditional study of electromagnetic theory is typically theoretical, abstract, and usually requires several semesters of study for developing a useful proficiency. Consequently advanced study is usually required in addition to introductory level work. Also, the traditional E&M lecture pedagogy does not resonate with modern engineering students. Typically these students have very little practical experience in engineering or in visualizing the mathematics of field related quantities. Hence a theoretically based introduction to E&M often ends most E&M careers. The rigors of E&M, in combination with an exponentially increasing knowledge base, often results in the study of E&M being postponed until graduate school. However, this is not an option at UST. Since a substantial amount of time is dedicated to E&M and since undergraduate credit hours are precious, the challenge was to develop an E&M pedagogy that imparts an applied E&M learning experience without significantly increasing the number of contact hours and which maintains interest. Hence the need and opportunity exists for a careful re-evaluation of the E&M skill set obtained from the full-year sequence. The result was the development a modular E&M pedagogy that emphasizes metrology and practical laboratory skills with sufficient theory to understand the basis for these measurements. Finally, ABET accreditation involves (among other things) the implementation of processes for performing outcome assessments and an overall system for meeting accreditation requirements along with continual improvement[3]. At UST these systems are used to help assess the attributes of our ‘deliverable’ (i.e. our graduates) and track their performance over time. In particular, these systems are being used to monitor the long-term impact of our modular E&M teaching pedagogy.

In order to develop a perspective, understanding and foundation for how E&M is generally taught, many sources were queried and evaluated. This included visits to several E&M laboratories, numerous discussions with employers and colleagues whom currently teach E&M, discussions with IAB members, years of industrial experience in applying E&M theory, and interdepartmental committee work between physics and engineering on the E&M course. This provided the starting point for answering questions such as, “What E&M skills do we want our students to have?”, “What is our final product?”, and “Where do our graduates go to work?”

Since the study of E&M has been active for over a century, the approaches used by other institutions to teach and integrate their undergraduate, graduate, and laboratory curricula were studied. A very useful list of 'Universities' Electromagnetics Research Groups' can be found at the web site of the University of Illinois, Urbana[4]. A majority of the research groups located in the continental United States that are identified on this web page along with several additional E&M centers were queried in a mailing regarding their E&M teaching pedagogy. Several of the questions in the introductory letter sent to these institutions are summarized in the following table.

Table 1: Investigatory questions

➢ Describe the E&M teaching pedagogy at your institution?
➢ How is your E&M laboratory organized?
➢ What is the optimal number of students in an E&M lab?
➢ What type of equipment is used in your E&M labs?
➢ What is the supporting cost structure for the E&M lab?
➢ Describe the trials-and-tribulations of your E&M lab experiences.
➢ Describe the activities and actions that worked in the E&M laboratory.
➢ Describe the activities and actions that did not work in the E&M laboratory.
➢ What other experience can be shared regarding your E&M labs?

All of the respondents were contacted and subsequently phone interviewed. As a follow-up to the phone interview, several E&M laboratories were visited. These included the E&M laboratories at Rochester Institute of Technology[5], the E&M laboratory at Saint Cloud State University[6], and several smaller E&M laboratories at the University of Minnesota[7, 9]. Each laboratory typically emphasized a subset of the many possible areas of E&M study. In addition, it was very useful to directly discuss the various E&M teaching pedagogies, approaches, philosophies, and obtain hands-on-experience with the various experimental setups and demonstrations used at these institutions. The experiments typically included various elements of transmission line theory, antenna theory, and RF theory. Overall these visits helped identify and clarify the level of complexity that undergraduate students could reasonably be expected to handle. In general, all of the E&M programs and web sites reviewed emphasized a similar set of introductory concepts and as the class sequences advanced, ultimately focused on the various specialty topics unique to the institution. The only significant variation in the various curricula was the sequence in which topics were covered. Generally speaking, there were two subject sequences in teaching E&M. The first approach followed the traditional sequence of statics, introductory electrodynamics, transmission lines and propagating phenomena such as antennas and wave guides. The second approach, proposed by Ulaby[8], introduces transmission line theory at a relatively early point in the topic progression and then rounds out the topics in a traditional manner. The philosophy behind introducing transmission line theory early in an E&M study is based on the observation that the necessary mathematical overhead is not burdensome and a bit of dynamics tends to promote and preserve student interest rather than having them 'suffer' through a semester long initial excursion of statics prior to dynamics. Since one of the main difficulties students experience in any E&M sequence is the simultaneous mastering of the required mathematics in real time with the nuances and implications of E&M itself, both of the above approaches stay within the boundaries dictated by the mathematical maturation process. The approach proposed by Ulaby was not adopted in this work due to difference in pedagogy philosophy.

Finally, the opinions and inputs from representatives of several companies found in the upper Midwest along with inputs from the IAB were actively solicited. Since the outcome-analysis-processes at UST are designed to assess the success of our graduates in the work place, corporate inputs are used to tune the overall UST engineering curriculum within the limits set by the ABET accreditation standards. The unanimous input from our corporate customers was that if anything, the need for students to understand E&M is becoming even more acute in the work place. Furthermore, the ability to perform measurements was considered more important than simply understanding theory. Hence the IAB and corporate inputs strengthened the case for developing an E&M teaching pedagogy that enables undergraduates to apply metrology and E&M theory in a laboratory environment.

Based on this investigation, several conclusions were drawn. With regard to general E&M knowledge, it was determined that UST graduates needed to command a basic understanding of at least the following topics:

- A view of E&M theory from a physics and engineering perspective
- Sources of electromagnetic noise and shielding methods
- Transmission line phenomena particularly with regard to high-speed digital system
- General antenna theory and antenna propagation patterns; e.g. for cell phone applications and WiFi.
- Basic plane wave phenomena such as reflection, transmission, and absorption characteristics at interfaces.

Surprisingly, there was almost no external demand for our undergraduates to understand general wave-guide theory. This was considered to be a more 'advanced' topic. With regard to applied skills, a basic proficiency in the following was considered desirable.

- Ability to perform E&M measurements
- Ability to use instruments such as:
    - Network analyzers for RF work; e.g. S-parameter and Smith Chart measurements
    - Spectrum analyzers
    - Microwave source generators
- Antenna pattern measurements
- Transmission line measurements
    - VSWR
    - Reflectometry
    - Matching
- Introductory ability to use E&M finite element software
    - ANSYS®
    - FEMLAB®

Results/pedagogy

Based on the research just noted, a modular metrology-based E&M pedagogy was developed for the second semester. Depending on assessment results, the approach may be extended to the first semester as well. The modular approach has four global objectives. The first is get students excited about E&M. The second objective is to develop a flow/flux based understanding of the vector calculus as applied to E&M and fluid mechanics. The third objective is to develop the applicable theory of several E&M topics enough so that laboratory measurement responses can be understood. The fourth objective is to develop an order-of-magnitude understanding of the of the appropriate field quantities in each module.

As the details of the metrology-based modular-pedagogy were formalized and distributed for preliminary peer review, an interesting observation was made by a colleague whom teaches graduate level E&M. Suppose a student continued their E&M studies after mastering the E&M skills just noted. The conjecture was made that this student would probably be better prepared for advanced E&M work than someone taught with the traditional E&M pedagogy[9]. Proving this conjecture is part of the on-going long-term assessment of the new pedagogy.

The first objective of the metrology-based modular-pedagogy is addressed through a variety of methods that include discussions on the history and discoveries leading to E&M, hands on laboratory experiences, and applications in industry. The other three objectives are developed through the topical arrangement of the modules. The course flow is summarized in table 2.

Table 2: Semester topics

First semester: statics – taught by the physics department with a physics perspective.
➢ Vector Calculus and coordinate systems ➢ E-fields: applications and boundary conditions ➢ B-fields: applications and boundary conditions
Second semester modules: taught by the engineering faculty with an engineering perspective
➢ Vector Calculus – flow/flux approach ➢ Introduction to dynamics and plane waves ➢ Transmission lines ➢ Antennas ➢ Finite element modeling

Note that the topics outlined in table 2 are traditional. The emphasis on developing applied E&M metrology skills with enough theory to understand the measurements using state-of-the art equipment without adding a lab section is new. Each module is designed to be covered in a 2 – 3 week period. The general module schedule is summarized in table 3.

Table 3: Module topics and time-line

Week	**Coverage**
1	Theory: lecture environment ➢ Supporting mathematics and theory ➢ Concepts ➢ Problem solving and learning exercises
2	Transition ➢ Theory conclusion ➢ Introduction to metrology in the lab
3	Self-directed laboratory work during the available lecture hours. No formal lectures

	occur during the third week. ➢ Laboratory support during class time ➢ Laboratory metrology ➢ Problem solving as needed to complete module experiments ➢ Summary report

The formal theory of each topic is introduced during the first week. During the second week the theory portion of the module is concluded and the discussion transitions to metrology, instrumentation, and laboratory practice. Laboratory work begins toward the end of the second week and concludes by the end of the third week. During the third week the laboratory activity is used to interactively demonstrate, reinforce and apply the lecture material toward typical systems applicable to the particular module. In addition, the laboratory exercises are designed to be self-directed so that an individual student, or small groups, can puzzle through the material at their own pace during the now-available lecture time allotted for the module once the instructor has covered the support material. The laboratory activity substitutes for traditional homework and the problem solving is directed toward achieving the laboratory objectives. The summary report helps the students develop scientific writing skills and focuses learning.

The first module covered in both statics and dynamics is vector calculus. A bit of background philosophy may augment the perspective on why this topic is covered at all. At UST E&M is a senior-level class. The mathematics prerequisites for the E&M sequence include the Calculus through multivariable and vector analysis. However, the students typically have difficulty in effectively applying the mathematics in E&M. Hence the objective of first module is to build on the formal mathematics training using the text by Schey[10] and presented using flux/flow concepts. This material is covered at the beginning of both semesters. The flow concepts of the vector calculus used in this short text along with the triply-redundant coverage of the material from the perspective of the math, physics, and engineering departments is designed to help the students develop an intuitive appreciation of E&M mathematics as well as a practical ability to apply vector calculus. Visualizing fields as a flow builds on the concept of representing an E&M field as the rate of a quantity flowing through a cross-sectional area. This concept is very 'Maxwellian' as well as being immediately transferable to fluid-flow, stress, and other force fields. After the math skills of the students have been 'honed' a bit, the next modules use texts that emphasize E&M from a physics or engineering perspective for the remainder of each respective semester. In statics, several texts have been successfully used by the UST physics department. The most successful text, based on student assessments, is the text by Griffiths[11]. Similarly several texts have been used to teach dynamics with an engineering perspective. Student assessment of these texts favors either Cheng[12] or Wentworth[13]. The text currently being used for dynamics was authored by Wentworth. This text was selected due to the emphasis on problem solving and visualization using the Matlab® [14] environment. Since Matlab® is used in several other classes by several other departments the use of Matlab® in E&M further develops and reinforces the students' skill at problem solving and visualization with this software.

Another module currently being used during dynamics is the finite element modeling module. Currently this module is based on the electromagnetic solver in ANSYS® 8.1[15] although

FEMLAB® [16] is also being evaluated for student use. The goal of this module, which is the final module covered in the semester, is to introduce the students to finite element software used in solving 'industrial grade' E&M problems. With the support of the ANSYS Corporation, an introductory student guide for solving electromagnetic problems was developed[17] as part of the grant work. The manual introduces the student to ANSYS® and then guides the students through the analysis of several topics that have already been previously covered during the course. For example, some of the topics covered in the manual include

- An introduction to the finite element method and discretization; i.e. meshing.
- An analysis of the full electric field surrounding a parallel plate capacitor
- An analysis of the external and internal magnetic field from a permanent magnet
- Modeling of a thin-film strip-line transmission system with various propagation modes
- Modeling the far-field transmission pattern of a simple antenna; e.g. the Yagi-Uda antenna.

These topics help reinforce field concepts as well as introducing the students to power and visualization capability of modern analysis code and graphical user interfaces (GUIs).

An example GUI output of the far-field pattern of an antenna array written in the Matlab® environment is illustrated in figure 1.

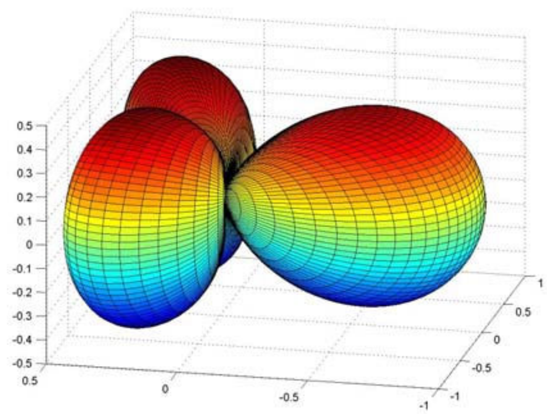

Figure 1: Far-field pattern from an antenna array

In the Matlab® environment this figure can be generated very quickly, is easily modified, and can be manipulated in all three dimensions to help the students visualize far-field antenna patterns. An example response from using ANSYS® to model, mesh, and analyze the far-field pattern of a Yagi-Uda antenna[18] is illustrated in figure 2.

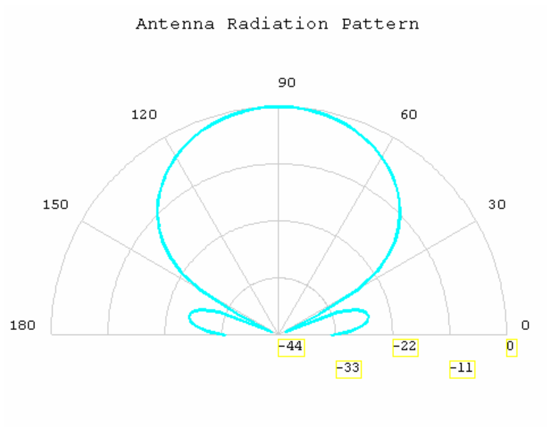

Figure 2: The polar plot of the far-field radiation pattern of a Yagi-Uda antenna.

At present, the theoretical portions of the transmission line and antenna modules have been developed. The laboratory equipment needed to complete the implementation of these modules has also been identified. In order to conserve laboratory space, each experimental laboratory station will have an associated portable equipment rack containing instrumentation and support electronics. The equipment racks will be stored and rolled out for use during the labs. The goal of the laboratory portions of these modules is to integrate metrology instrumentation supplied by Agilent[19] with core laboratory equipment and experiments supplied by Lab-Volt[20]. The basic equipment set for each station is summarized in table 4.

Table 4: Basic laboratory equipment set for the antenna and transmission-line modules

Item	**Unit**
1	Agilent N5230A Performance Network Analyzer (PNA)
2	Agilent time domain, calibration, cable, and frequency standard kits
3	Agilent 81104A, 80 MHz pulse generator
4	Lab-Volt Antenna Training and Measuring System 8092
5	Lab-Volt Transmission Line System 91028

The proposed frequency range for the transmission line and antenna modules lie in the 100 MHz to 10 GHz range. This frequency range was selected to enable bench-size experimental setups, which due to laboratory space limitations, would be difficult to implement at lower frequencies due to the associated wavelengths constraints. Lab-Volt supplies training systems, such as the transmission line and antenna systems, that can be readily adapted for use in university laboratories. Both Agilent and Lab-Volt often offer significant discounts for professional equipment for university use which from a cost perspective, is very important. Obtaining the equipment and laboratory systems is the subject of a joint interdepartmental Course, Curriculum, and Laboratory Improvement (CCLI) NSF grant application from several UST departments including Computer Science, Physics and the School of Engineering. The antenna and transmission line modules have been designed for 6 student stations and an instructor station. The student stations are designed for teams consisting of ideally 2, and at most 3 students. This results in a laboratory class size of 12-to-18 students plus the instructor. This class size is consistent with typical laboratory class sizes at UST. Multiple laboratory sections are usually added when the size of a class exceeds 12 students.

Discussion

The preliminary feedback from alumni and several companies that employ our graduates shows that the metrology-based modular approach of teaching undergraduate E&M is achieving the intended goals. The triply redundant flow/flux coverage of the vector-calculus module, the ANSYS® modeling module and the Matlab® field visualization GUIs are very popular with the students. These modules have succeeded in helping the students visualize and analyze real fields in practical applications as well as providing the graduates with industry recognized E&M skills. The main detractors of the modular approach are the costs and space associated with establishing an E&M laboratory. Hence support, via CCLI grant or corporate donations, is necessary for funding the complete E&M laboratory. The projected cost for implementing the experimental portions of the transmission line and antenna modules for the 7 laboratory stations is estimated to be on the order of $0.5 million dollars; hence the need for funding. Although these two modules could potentially be implemented in a less expensive manner at a longer wavelength, this could only be done by sacrificing experience in the use of modern E&M metrology equipment. There is also an intrinsic wavelength versus laboratory space consideration (i.e. shorter wavelength is better since less laboratory space is required for performing experiments). All things considered, the present goal is to operate the antenna and transmission-line modules in the low GHz frequency range so experiments can be performed on typical benches found in physics labs. The implementation details are pending and will ultimately be controlled by the degree of funding success. Site licenses for ANSYS® or FEMLAB® are also very expensive with costs reaching several tens of thousands of dollars per year depending on the number of seats. Fortunately 'multiple physics' software is used in a wide variety of mechanical and electrical applications at UST and is consequently viewed as a fundamental part of the overall engineering program. Hence the cost for this software is contained in the operating budget of the school. Overall, the modules implemented to date are working well and are providing undergraduates with E&M skills that are useful in industry after graduating with a B.S. degree.

Conclusion

A metrology based modular pedagogy for teaching undergraduate electromagnetic field theory to undergraduate students has been presented. The pedagogy simultaneously addresses the needs of students that graduate with bachelor degrees and then enter the work force along with the expectations of their potential employers. The pedagogy emphasizes understanding the basic theory associated with the various module topics and the application of this theory in a laboratory environment to cases that commonly occur in practice using metrology equipment typically found in industry. Based on preliminary alumni and corporate feedback, this pedagogy is achieving its objectives by providing engineering and physics students that graduate with a B.S. degree useful E&M knowledge and metrology skills.

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