A Capstone Design Project Based on Optical Frequency Domain Reflectometry (OFDR): A Comprehensive Undergraduate Research Project

Jacob Watts
Department of Electrical and Computer Engineering
Weber State University
Ogden, Utah, USA
jacobwatts@mail.weber.edu

Jared Beh
Department of Electrical and Computer Engineering
Weber State University
Ogden, Utah, USA
jaredbeh@mail.weber.edu

Shellee Dyer
Department of Electrical and Computer Engineering
Weber State University
Ogden, Utah, USA
shelleedyer@weber.edu

***Abstract*— This research-to-practice paper presents a novel capstone project for electrical and computer engineering students. It encompasses a broad range of electrical and computer engineering, including lasers and fiber optics, signal processing, analog circuit design, python programming, metrology and measurement uncertainty, and remote instrument control using GPIB and/or LAN. This broad range of topics gave the students an excellent opportunity to demonstrate, expand, and solidify the knowledge and skills from their undergraduate coursework. In addition, it also introduced the students to undergraduate engineering research. Prior publications on undergraduate research have demonstrated that it is invaluable to student self-efficacy and future success. However, prior publications on undergraduate research have also demonstrated the challenges of inexperience, short time frames, and limited resources, which are often exacerbated by the limited research resources available at a teaching-focused institution. Another challenge is the lack of technical elective experience: students usually take most of their technical elective coursework immediately prior to graduation, and limited resource require that most institutions must rotate which technical elective courses are offered in each semester. Both factors make it unlikely that undergraduate students will have had the opportunity to take the relevant technical electives prior to embarking on their undergraduate research. In this work, those challenges were overcome using a combination of regular one-on-one faculty mentorship and independent study by the students, as recommended by prior publications on undergraduate research. Additionally, the project was shaped and informed by many years of faculty experience as a Research Undergraduate Experience (REU) mentor to a large number of undergraduate students at a major national lab. In this project, students started with a comprehensive literature search to understand the state-of-the art in the field. The students had prior experience in literature searches for many of their courses, but this was the first time they had taken that information and incorporated into their own research project. The students created software to control the laser, and they designed, tested, and built detection and filtering circuitry. Additionally, the students implemented their knowledge of signal processing to convert the measured frequency-domain data to time-domain information. Finally, the students determined the uncertainty of their measurements by comparing measurements of a microscope slide to a standard reference (a physical caliper measurement). Although this project used an expensive tunable laser, that is not strictly required to implement this project, and this paper will also present ideas for a similar project implementation with inexpensive, commonly-available components, such as a white light source and smartphone camera.**

Keywords—capstone projects, electrical engineering, undergraduate research

I. Introduction

The capstone senior design project is a critical but challenging piece of undergraduate engineering education. Some key learning outcomes include the ability to design and conduct experiments, the ability to apply knowledge gained from prior coursework, the ability to work on diverse teams, the ability to communicate effectively, and management of a complex project in a limited time frame. However, the senior design project is often challenging for students, because it is often the first-time time they tackle large-scale, long-term projects, often with a lack of an end-to-end, high level view of the project [1].

This paper aims to explore the integration of undergraduate engineering research into senior capstone design projects. The goal is to improve the learning outcomes, focused in particular on areas of technical knowledge, team work, technical confidence, and self-efficacy of the students.

Undergraduate research is known to have many benefits: exposing students to the research process leads to a deepened technical knowledge, strengthened view of themselves as engineers, emulating the patience, persistence, and initiative of seasoned researchers [2]. Most undergraduate researchers report that the experience lead to increased understanding of the research process, increased self-confidence in their research skills, and increased awareness of the demands and rewards of graduate school [3].

One clear theme from the literature is that good mentoring is fundamental to successful undergraduate research [4]. This project draws on the PI's 10+ years of experience in mentoring undergraduate research at a major national lab. Integrating undergrads into research is particularly challenging because of their lack of experience, but regular (weekly or more often, as needed) meetings with a mentor can ameliorate some of these difficulties. These regular meetings have been identified as one of the cornerstones of mentoring undergraduate researchers, along with strategic pre-planning, clear and well-scaffolded expectations, teaching technical skills, balancing rigorous expectations with a strong working faculty-student relationship, building community in the team, one-to-one, hands-on mentoring, and facilitating students' professional networks and research dissemination [5].

The goal here is to compare the learning outcomes for senior capstone students who completed an undergraduate research project for their senior design capstone to students who completed a more traditional (non-research oriented) senior design project. The project that we chose was Optical Frequency Domain Reflectometry (OFDR), which has a broad range of applications from fiber optic sensors to characterization and monitoring of photonic components. This project requires a diverse range of technical knowledge, including interferometry, signal processing, circuit design and testing, fiber optics and lasers, and software design for controlling equipment. This project was chosen because of the PIs research history, which includes years of prior experience and several publications in the area. It was also chosen because of the promising opportunities to extend the work in future directions, including to fiber optic shape sensing, optoelectronic device characterization, and novel material characterizations.

II. Approach

A. *Literature Review*

The literature review is an essential cornerstone of any research project. Most undergraduates gain experience in this area through one or more undergraduate classes, but that experience does not always apply directly to the challenges of undergraduate research. Many publications are written for an audience of experts, and that does not translate directly into the background and skills of undergraduate students. Most students will benefit directly from mentor guidance at this stage and will need direction and support in identifying key publications and understanding results. Most students should start with relevant review papers on the topic, as those papers often more accessible to the non-expert in the field. Through their literature review, the students were able to identify several relevant review papers to help get them started in the project [6,7].

B. *Proposals*

Writing proposals is an essential, but sometimes unwelcome part, of the research process. The students involved in this project wrote two proposals: one for the department faculty to clearly outline the goals and expected outcomes, and one to the local office of undergraduate research. The faculty proposal had to be signed by all department faculty, and that is an important step to ensure that all parties involved have agreed to clear and consistent outcomes. The students wrote a proposal to the local office of undergraduate research (OUR), which was funded. Most of the expensive equipment required for this project was already in place, but the OUR money allowed the students to cover some of the small electronics and optical components that were needed over the course of the project.

C. *Tranining*

Training is an essential piece of successful undergraduate research, and one that should be considered an essential piece of good mentoring. The students in this project had no prior experience with lasers, so a laser safety tutorial was required. Additionally, the students were trained on proper usage of a fiber fusion splicer, tunable laser, and optical spectrum analyzer. Additional training about interferometry and fiber optic components was provided on an ad hoc basis throughout the project, primarily during the weekly team meetings.

D. *Preliminary Design Review*

The students' OFDR is shown in Fig. 1. It consists of two Michelson interferometers: a measurement interferometer which includes the device under test (DUT) and a reference interferometer. As the wavelength of the tunable laser is swept from 1490-1640 nm, the detector sees a series a constructive and destructive interference fringes. The reference interferometer is used to compensate for any nonlinearity in the laser sweep. The high pass filters (HPF) are used to separate the interference fringes from the baseline DC offset. The data was digitized with a 16-bit digital-to-analog converter (Dataq) and stored in a computer for signal processing. This gives measurements in the frequency domain (interference data vs. wavelength), and to obtain time-domain information requires an inverse Fourier transform. Prior to the Fourier transform, the data must be correct for any nonlinearities in the laser sweep using the data from the reference interferometer. The students design included an understanding of the tradeoffs involved in choosing the optical path length differences for the two interferometers, the electronic design of the HPFs and optical receivers, and designing and programming the GUI to control the entire system.

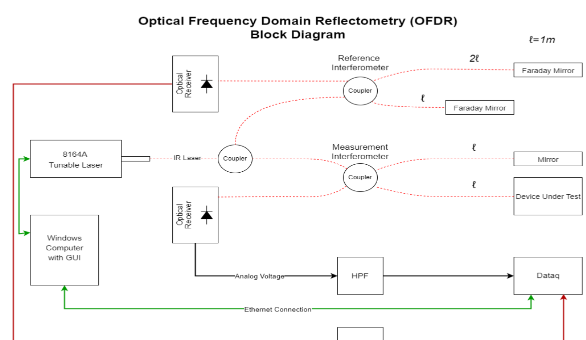

Fig. 1 System Design. The source is a tunable laser, the dashed red lines are fiber optic cables, the couplers are fiber optic beamsplitters. HPF: high-pass filter. Dataq: analog-to-digital converter.

E. *Testing and Verification*

Testing and verification are essential steps that are often underestimated. Most students do not set aside enough time to test their projects as well as time to correct for any problems that arise during the testing phase. The PI's expertise includes metrology, gained from 20+ years at the National Institute of Standards and Technology; therefore, system validation was a key focus of this project. For validation, a microscope slide was used. This provides a sample with well-known refractive index and a thickness that can be measured separately using a digital caliper. The results are shown in Fig. 2. In this example, six measurements were taken for six different distances between the fiber endface and the microscope slide (DUT), shown in the six different colors. For each measurement, there are two interferograms: created by the Fresnel reflections at the front and rear surfaces of the microscope slide. The spacing between the two interferograms is set by the optical path length of the microscope slide, and, given an accurate refractive index, it is possible to determine the thickness of the microscope slide and compare it to the digital caliper measurement. These results are shown in Table 1. For comparison, the digital caliper determined the thickness of the slide to be 1.04 mm. At the initial stage of the project the students had set a measurement uncertainty goal of +/- 0.5 mm, and that goal was exceeded by the results.

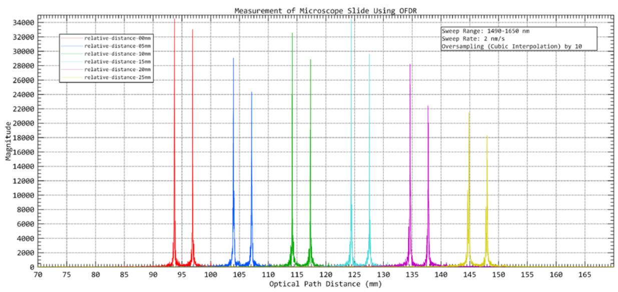

Fig. 2 Measurement results when a microscope slide was used as the DUT. Each color represents the data collected for a different distance between the fiber endface and the device under test. Focusing on a single color, there are two clear interferograms: one created by the backreflection from the front surface of the slide and one from the rear surface of the slide.

TABLE I. SYSTEM VERIFICATION. THE MICROSCOPE SLIDE THICKNESS WAS CALCULATED FROM THE INTERFEROGRAMS SHOWN IN FIG. 2 FOR EACH DATA SET (RELATIVE DISTANCE FROM THE FIBER ENDFACE). FOR COMPARISON, THE DIGITAL CALIPER INDICATED THAT THE MICROSCOPE SLIDE THICKNESS WAS 1.04 MM (+/-0.1 MM UNCERTAINTY, FROM THE CALIPER MANUFACTURER).

Relative Distance (mm)	Calculated Width (mm)
0	1.04
5	1.04
10	1.04
15	1.04
20	1.04
25	1.04

III. DISCUSSION

One goal of this project was to demonstrate improved learning outcomes for undergraduate research compared to traditional senior projects. All graduating seniors are requested to complete a self-assessment of the learning outcomes from their undergraduate career. This provided a useful metric to compare the students involved in this project to their classmates. The students had the option of completing the survey electronically or traditional paper and pencil. The survey questions as shown in Table II.

TABLE II. SURVEY QUESTIONS FOR GRADUATING STUDENTS. THE SURVEY QUESTIONS ALL BEGIN WITH "THE WSU ELECTRICAL AND COMPUTER ENGINEERING PROGRAMS PREPARED YOU TO ACHIEVE THE FOLLOWING OUTCOMES:" STUDENTS' RESPONSES WERE ON A SCALE OF 1-5, FROM STRONGLY DISAGREE TO STRONGLY AGREE.

A.	An ability to apply knowledge of mathematics, science, and engineering.
B.	An ability to design and conduct experiments, as well as to analyze and interpret data.
C.	An ability to design a system, component, or process to meet desired needs with realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability.
D.	An ability to function on multidisciplinary teams.
E.	An ability to identify, formulate and solve engineering problems.
F.	An understanding of professional and ethical responsibility.
G.	An ability to communicate effectively
H.	The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental and social context.
I.	A recognition of the need for, and ability to engage in, life-long learning
J.	A knowledge of contemporary issues
K.	An ability to use the techniques, skills and modern engineering tools necessary for engineering practice.

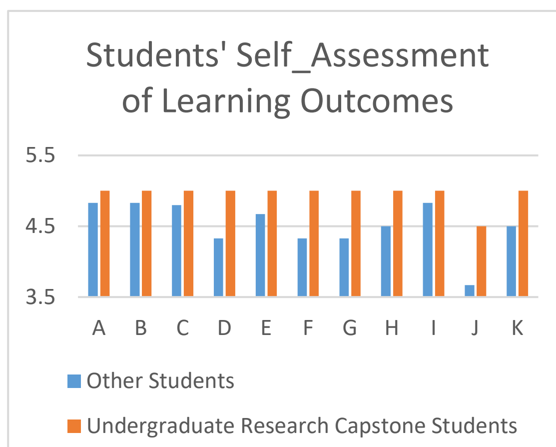

Fig. 3. Students' self-assessment of learning outcomes from their undergraduate studies. Compares the students engaged in this undergraduate research project to their peers. The x-axis labels A-K refer to the questions listed in Table II.

The survey results, comparing the self-assessment of learning outcomes for the students on this research project compared with their peers is shown in Fig. 3. Although there is a clear and marked improvement in the self-assessment of the students involved in this project (shown in orange) to their peers (shown in blue), it is important to note that the students were asked to assess the learning outcomes from their entire undergraduate career, and not just the senior capstone design portion. Furthermore, the data could be biased by the fact that undergraduate research tends to attract the students who are strongly motivated to achieve the best possible educational outcomes. Additionally, the sample size was small and included only eight students total, so that we could compare to peer classmates who had similar experiences, including the educational disruption created by a global pandemic. More data is needed in order to make broad conclusions. However, this result is consistent with prior results indicating improved learning outcomes for undergraduate researchers [2,3]. Crucial to the improvement in learning outcomes is long-term of more than two semesters, similar to the time frame of a senior design capstone project.

Although this project used an expensive tunable laser, it is possible to create a similar project using an inexpensive white-light bulb. The tuning of the laser wavelength, in that case, would be replaced with an optical spectrometer. Optical spectrometers can be expensive, but it is possible to design an inexpensive spectrometer using a smartphone camera [8]. Incorporating smartphones into engineering education is an intriguing was to enhance education with the significant financial investment of traditional laboratory equipment. These devices provide a mobile pocket-sized engineering laboratory. Most students already own at least one mobile device, and most students are excited about learning new applications of these devices [9-10].

In summary, we have demonstrated improved learning outcomes compared with their peers for a small group of students who replaced a traditional senior design project with an undergraduate research project. Engaging in undergraduate research leads to improve technical learning, team building, communication and self-confidence. Future students will extend this project to metrology and sensing applications.

References

[1] J. A. Flores, O. H. Salcedo, R. Pineda, P. Nava, "Senior project design success and quality: a systems engineering approach," Procedia Computer Science, vol. 8, pp. 452-460 2012, ISSN 1877-0509, https://doi.org/10.1016/j.procs.2012.01.085.

[2] M. C. Linn, E. Palmer, A. Baranger, E. Gerard, and E. Stone, "Undergraduate research experiences: impacts and opportunities," Science, vol. 347, 1261757-1-6, 2015.

[3] S. H. Russell, M. P. Hancock, and J. McCullough, "Benefits of undergraduate research experiences," Science, vol. 316, no. pp. 548-549, (2007).

[4] S. Lekhakul and R. A. Higgins, "Senior design project: undergraduate thesis," in IEEE Transactions on Education, vol. 37, no. 2, pp. 203-206, 1994, doi: 10.1109/13.284995.

[5] J. O. Shanahan, E. Ackley-Holbrook, E. Hall, K. Stewart, and H. Walkington, "Ten salient practices of undergraduate research mentors: a review of the literature," Mentoring & Tutoring: Partnership in Learning, vol. 23, (5), pp. 359–376, 2015. https://doi.org/10.1080/13611267.2015.1126162

[6] Z. Ding, C. Wang, K. Liu, J. Jiang, D. Yang, G. Pan, Z. Pu, T. Liu, "Distributed optical fiber sensors based on optical frequency domain reflectometry: a review," Sensors, vol. 18, pp. 1072, 2018 https://doi.org/10.3390/s18041072

[7] C. Liang, Q. Bai, M. Yan, Y. Wang, H. Zhang and B. Jin, "A comprehensive study of optical frequency domain reflectometry," in IEEE Access, vol. 9, pp. 41647-41668, 2021, doi: 10.1109/ACCESS.2021.3061250.

[8] A. Das, A. Wahi, A., I. Kothari, and R. Raskar, "Ultra-portable, wireless smartphone spectrometer for rapid, non-destructive testing of fruit ripeness," Sci Rep, vol. 6, pp. 32504, 2016. https://doi.org/10.1038/srep32504

[9] R. Hurd and D. Grote, "Smartphone-based labs for engineering vibration class," in ASEE Rocky Mountain Section Conference, Golden, CO, 2023.

[10] S. Dyer, "Using mobile devices to improve engineering education: a process control laboratory example," in ASEE Zone IV Conference, Boulder, CO, 2018.