Final Performance Report

N000141912713 : ROTC Research Experiences in Naval Electronic Warfare (RENEW)

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14. ABSTRACT
This report summarizes the Research Experiences in Naval Electronic Warfare (RENEW) project completed at NC State University. The project consisted of 4 major activities which are described herein: (1) Development and delivery of two weeklong workshops on EW, RF, and radar, (2) Undergraduate research in EW, RF, and sensing, (3) Development and delivery of a semester-long Electronic Warfare Systems course, and (4) Development and mentoring of a senior design project on a 60 GHz radar system.

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Accomplishments

What were the major goals and objectives of the project?

Objective 1: Increase exposure to and knowledge about electronic warfare topics for ROTC students and other US undergraduates.

- Strategy 1.1: Develop hands-on summer workshops for ROTC students. One workshop will be based on a workshop series on radio systems delivered at conferences around the world by co-PI Ricketts. They will be customized so that students research and implement EW strategies. Topics will include radio systems, radar, and electronic warfare. ROTC students from NC State and other universities will be invited to attend with support.
- Strategy 1.2: Develop EW-oriented final year design projects for NC State ECE seniors while seeking to involve ROTC students on the team.

Objective 2: Provide undergraduate research experiences related to RF electronics, EW, and sensing.

- Strategy 2.1: Mentor NCSU ROTC students and other US undergraduates on cutting edge research problems in EW, RF electronics, and sensing during the academic semester and summer. The PIs have active research programs in microwave and millimeter wave systems, electromagnetics, and antennas. We will seek to involve four students during each academic semester and create a more team-based research environment during the summer involving up to 10 undergraduate students. The students in the summer program will work on small teams to conduct research on EW-related topics and will present their research outcomes in a short seminar at the end of their research effort.

Objective 3: Expose NC State ROTC and other defense-oriented US undergraduates to US military needs and technical career paths.

- Strategy 3.1: Provide NCSU and other local ROTC students several hands-on seminars and site visits to explore the realities of technology development, integration, and deployment in the military environment led by former military operators.
- Strategy 3.2: Identify summer undergraduate research opportunities at Navy and other DoD facilities and connect them to NC State ROTC students. Many federal scientists we interact with are eager to bring on new US engineers. The momentum of this program provides an opportunity to develop interest among the participants in the types of technical challenges that these STEM professionals face.
- Strategy 3.3: Integrate this program with an ongoing effort led by co-PI Steer to create a program in electronics forensics leading to a bachelor of science in electrical and/or computer engineering, or computer science, for special forces (SF) operators. Coupling the planned cohort of 20 SF operators from Fort Bragg and Virginia Beach with ROTC personnel on a pilot basis provides a viable group of students that justify an effort to adapt the curriculum. Distance and asynchronous delivery of course content are inherent to the SF program and this will enable elements of our program to be delivered to other ROTC sites in the future.

What was accomplished towards achieving these goals?

As much of the originally proposed work involved undergraduates, large teams, workshops, and some group travel, elements of this project were adjusted to meet the public health requirements. While some undergraduate research activities were able to proceed as planned with minimal group interaction, the larger in-person summer research experiences were canceled. However, by far the largest effort during the reporting period was converting the planned in person workshop to a virtual one and preparing content and materials for the event.

Below we list the major activities conducted under this grant since the project's inception in Fall 2019 and summarize the key outcomes.

I. Major Activities and Outcomes:

A. Activity 1: July 2021 Summer Workshop

The largest single activity under this program was the development of the Research Experiences in Naval Electronic Warfare (RENEW) Virtual, Hands-On Workshops. While these were originally planned to be in person during the summer of 2020, they were eventually moved to a virtual format due to COVID-19. Thus, new educational material and guided laboratories, including a completely new course on software defined radio, intended to introduce non-ECE students to wireless systems and electronic warfare, were developed.

Two weeklong workshops were offered in July 2021: a workshop for upper-class ECE students, "Build a Radar in a Week: System Theory & Design of Modern Radars" and an introductory workshop non-ECE students and underclassmen, "Introduction to Radio Systems & Software Defined Radio (SDR)". The events solicited applications from students using a website[1] developed by the PIs, and nearly every ROTC program in the country was individually contacted to invite their cadets. We received more than 60 applications, and these were evaluated to select 45 students who were assigned to the event that best fit their experience level. Low cost lab kits were prepared at NC State and sent to these students. The events were held as live video meetings on Zoom that occupied most of the day for five days (with appropriate breaks). Lectures were followed by guided laboratories in which students simulated and fabricated circuits or programmed and measured signals with software defined radios using the lab kits provided. Over 90% of the invited participants attended their weeklong event.

In addition to the lecture and lab materials presented, guest speakers from NRL, NIWC-Pacific, Naval ROTC, and a local defense technology company provided excellent seminars to give the students real-world context for their studies.

[1] https://conference.ece.ncsu.edu/renew/

Outcomes: July 2021 Summer Workshop

All of the participants were US citizens. Due to the small number of ROTC students in engineering, a high degree of effort was put into advertising the program to ROTC cadets. We contacted 174 representatives from ROTC programs around the country with information about the workshop and requested that they invite their cadets. A total of 45 students from 15 different US universities attended the workshop. Students attended from 13 states: NC, OH, TX, PA, OK, FL, CO, SC, DC, WI, GA, NJ, and CA. We also found success in recruiting a broad and diverse participant group. A detailed breakdown of the demographics of the participants is given in Fig. 1.

To assess the effectiveness of the workshops, we asked students to rate their knowledge, self-efficacy, and career interest in several technical areas on a scale of 1-5 (5 being best). Anonymous ratings were taken just before and just after each workshop to measure the change. Figs. 2 and 3 show how students rated their knowledge, self-efficacy (i.e., ability to apply the knowledge) and career interest in several areas. After the introductory workshop (intended for non-ECE majors and early stage ECE students), student ratings on these events increased dramatically. The average "knowledge" rating doubled from 2.0 to 4.0. The self-efficacy rating went from 2.6 to 3.7, and the career interest rating went from 3.7 to 3.9. Following the second workshop, intended for more experienced students, the knowledge and self-efficacy scores increased by 0.5 and 0.4, respectively, while the career interest scores remained flat on average.

Clearly, students with less knowledge felt that they learned more than those with prior experience did. Thus, we believe these tools are best aimed at mid-stage students at the sophomore and junior level who are just beginning to think about their senior electives and career choices. The workshops are less effective for those who have already had advanced coursework in relevant topics. Also, we observe that the workshops reached a body of students who were already very interested in careers in defense and security-related topics, which was expected because of the extracurricular nature of the events and the way they were advertised to students. Despite the high level of interest in these careers, on average, the events further increased their interest in this areas.

We received many positive comments from the participants. A few are quoted below:

- *"The workshop was well developed, organized, and polished. All the lecturers and speakers presented interesting content at an understandable pace. The guest speakers were great and allowed me to learn about opportunities that I was unaware of or had not considered. The labs were fun and helped me "see" the concepts in action. I greatly appreciate being provided with hardware as well as the virtual nature of the workshop; this allowed for hands-on experience and a diversity of perspectives without the expense of travel. I would definitely be interested in future workshops on related topics."*
- *"I put "great deal of knowledge" on all not b/c I think I have a lvl 5 of knowledge I could have, but because that's how much I feel I've learned this week. The breakdowns and explanations were amazing, and the hands-on application really sealed it in."*

- *"I like the organization of the lecture notes. The professors did a very good job at condensing the information in the time span that we had. The speakers were a good addition to the workshop because it provides insight on the efficacy of EW and how people apply these concepts I'm learning in a more sophisticated manner. Humbling experience to know that I have a ways to go from the professors and speakers"*
- *"The class taught my a great deal of what goes into radar system. I did not know what to really expect coming into the workshop. AWR was a program that I never heard of and pick it up really quickly on how to use it…After going through this, I would recommend to anyone looking to work in RF even if it means traveling to NC State to do it."*

Overall, the virtual hands-on format was more successful than we initially anticipated. Students were able to use the hardware kits and laboratory instructions with relatively good success. Thus, the workshop did help advance our knowledge of developing virtual learning tools that may find application in today's hybrid meeting format. That said, the PIs believe that an in person event is always going to be the most effective for this type of activity and are seeking other opportunities to expand and deliver these materials.

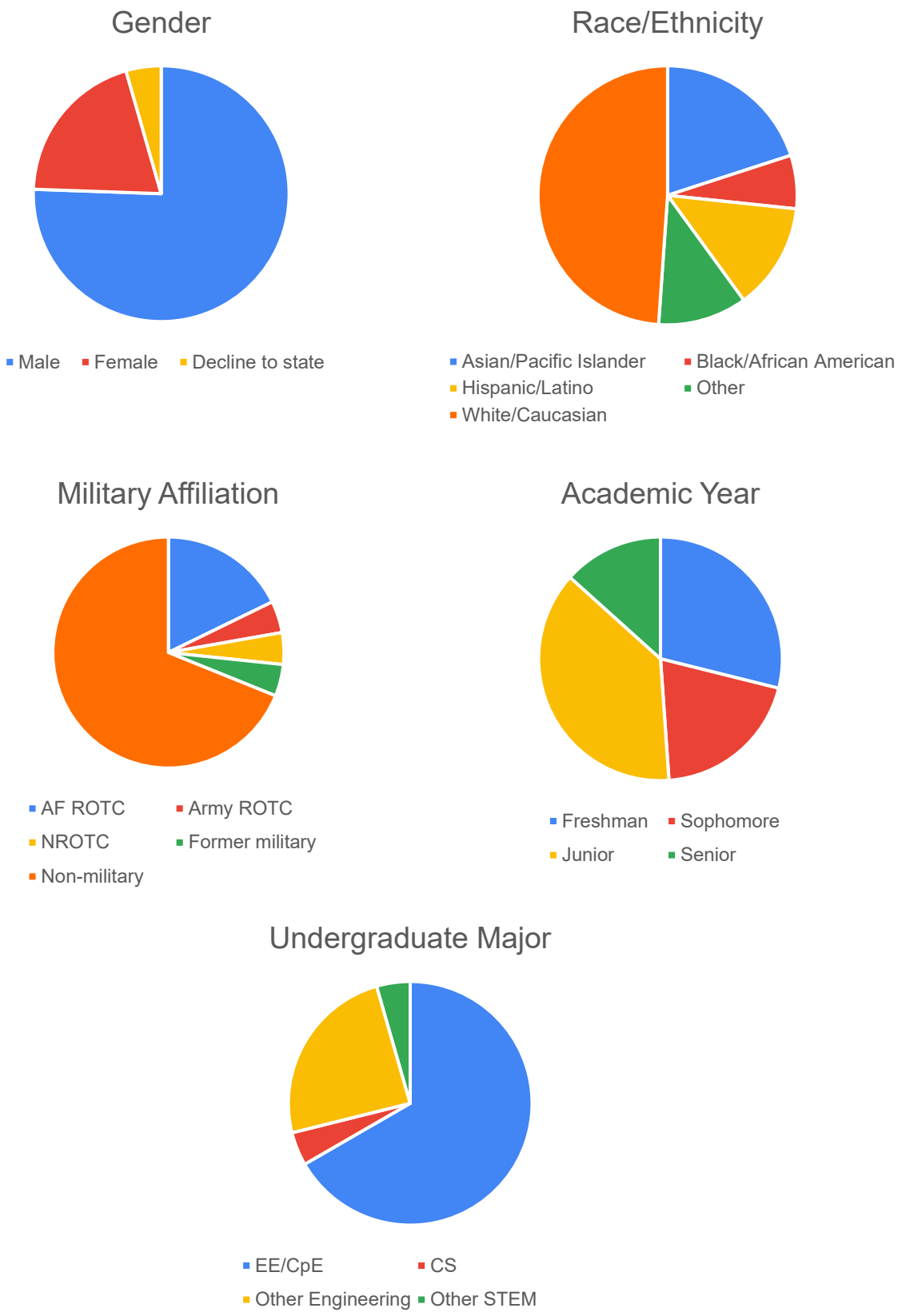

Fig. 1 – July 2021 Workshop participant demographics.

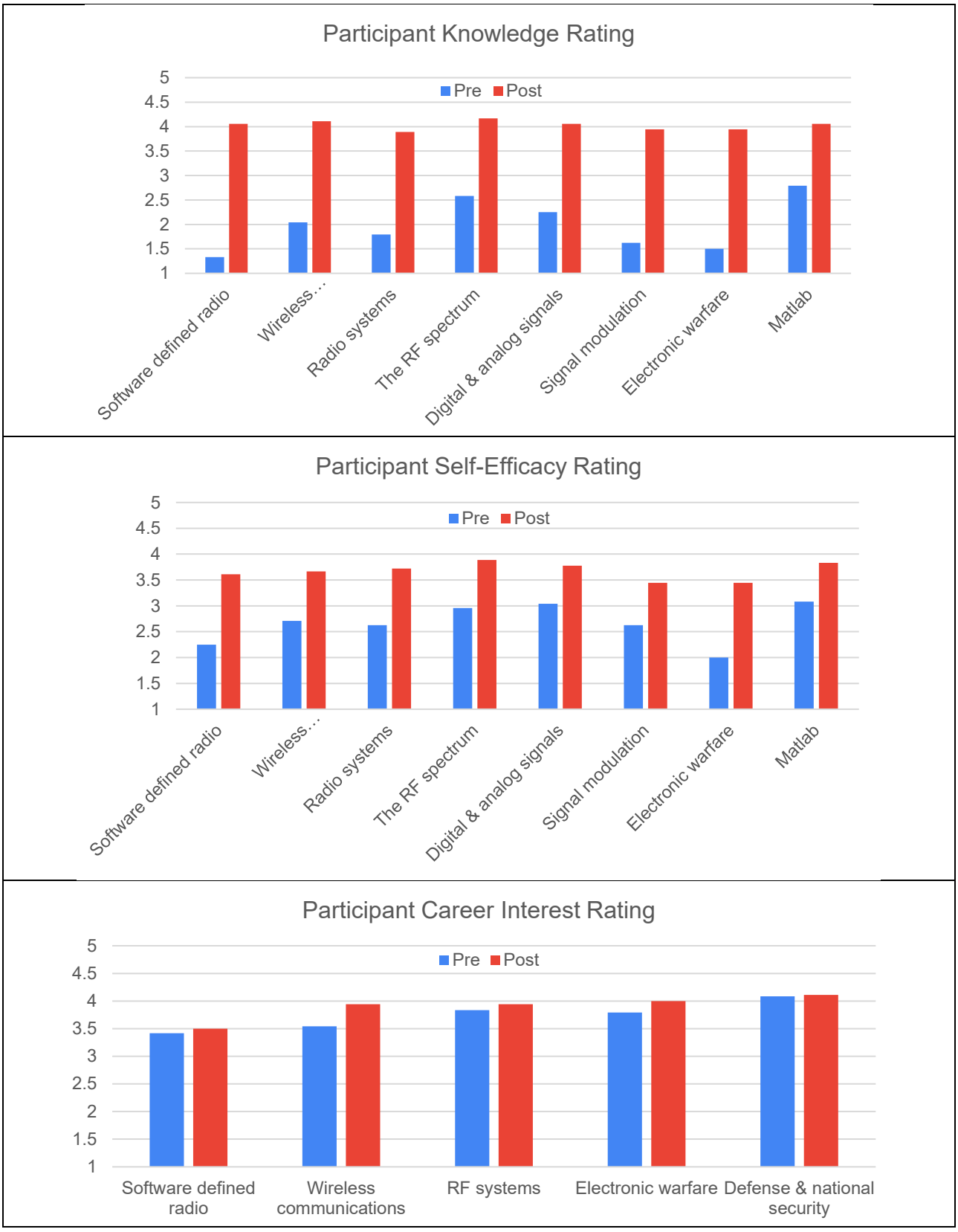

Fig. 2 – Knowledge, self-efficacy, and career interest ratings before and after the Introductory Workshop

Fig. 3 – Knowledge, self-efficacy, and career interest ratings before and after the Intermediate Workshop

B. Activity 2: Undergraduate research in EW, RF, and sensing.

Over the course of the project period, fourteen undergraduate students were recruited to work in the PIs' research labs on topics related to RF engineering, sensing, and EW. Of the students who participated, five were also in NC State's ROTC programs (three from the Naval ROTC and two from Army ROTC) and one student had served in the US Coast Guard. Some students participated for only a few weeks due to their other commitments allowed while others participated for over 2 years.

As with most universities, the NC State campus remained closed for non-essential workers during the March 2020 – June 2021 period due to COVID-19 restrictions. This made on-boarding and mentoring undergraduate students somewhat difficult during this period. However, students were able to complete several projects over the project duration. Some of the student efforts were directed towards research activities while others related to the development of educational material for the EW Systems course and summer workshops. In these projects, students worked on various tasks including literature review, computer simulation, software development, testing and measurement, and PCB fabrication.

Outcomes: Undergraduate research in EW, RF, and sensing.

Several projects were completed under this first activity, and some are still underway. At the end of the Spring 2020 semester, student teams gave Zoom presentations summarizing their work. These have been stored on Google Drive for download[2]. Brief summaries of several of the research projects are given below.

1) Development of 1 GHz and 2.4 GHz radar electronics for radar and EW workshops

UGs designed a new IF data acquisition board for use with an audio jack and computer. This PCB will allow students to test their radars with their own PC. This is used for both workshop events related to radar fabrication as well as a course project. In addition, the students tested the 1 GHz and ISM-compatible 2.4 GHz radars and updated the Matlab code for plotting the radar returns. This work has been essential to the development of the virtual workshop material. An image of several of the fabricated components is shown in Fig. 4.

2) Characterization of RF switches for time-varying antennas

One UG student worked on the simulation and layout of circuit elements for modeling a time-varying antenna system. He learned how to run simulations in Keysight ADS software and layout boards in Autodesk Eagle, fabricated boards with an Othermill Pro, and measured the characteristics of his boards. Over the course of the project, the student encountered challenges related to component and board parasitics which offered a useful learning experience about high frequency design. He also assisted with measurements of a time varying antennas. This work

[2] https://drive.google.com/file/d/1_LaUaM32ETryVzSEZma0GnOH0_b02Kw1/view?usp=sharing

resulted in a publication[3] in *IEEE Transactions on Microwave Theory and Techniques*, upon which the UG student, an Army ROTC cadet, was a co-author.

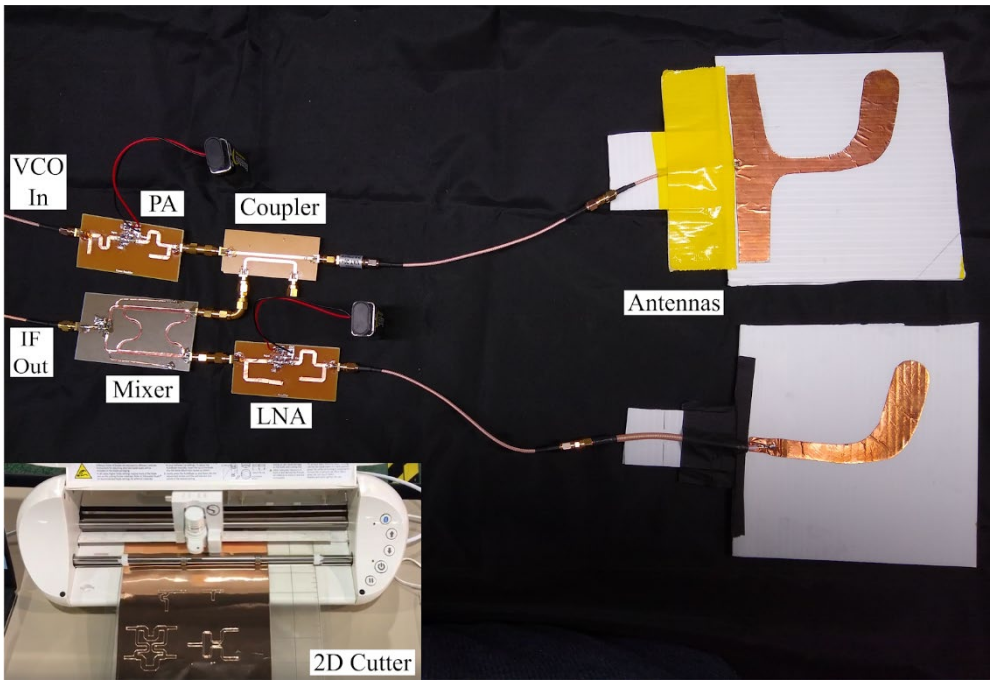

Figure 4: Fabricated radar components

3) Simulation of unit cells for gradient index lenses 3D printed zirconia

One UG student learned how to use Ansys HFSS software for electromagnetic simulation. He learned to create periodic boundary conditions to simulate the effective permittivity of unit cells composed of a shaped ceramic material. The student investigated the effect of differing shape on the effective permittivity of the unit cells, compared the structure's permittivity to composite mixing rules, and developed new types of unit cells to achieve both very high as well as very low permittivity values. The UG worked with a graduate student to design unit cells with different geometry for a complete "gradient index" microwave lens as shown in Fig. 5. The lens was printed using a state of the art additive manufacturing technique and measured. The student is a co-author on a paper that is being drafted about the device.

[3] D. Huang, K. Schab, J. K. Dusenbury, B. Sluss and J. J. Adams, "DC-Assisted Stabilization of Internal Oscillations for Improved Symbol Transitions in a Direct Antenna Modulation Transmitter," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 1, pp. 587-596, Jan. 2022, doi: 10.1109/TMTT.2021.3103209.

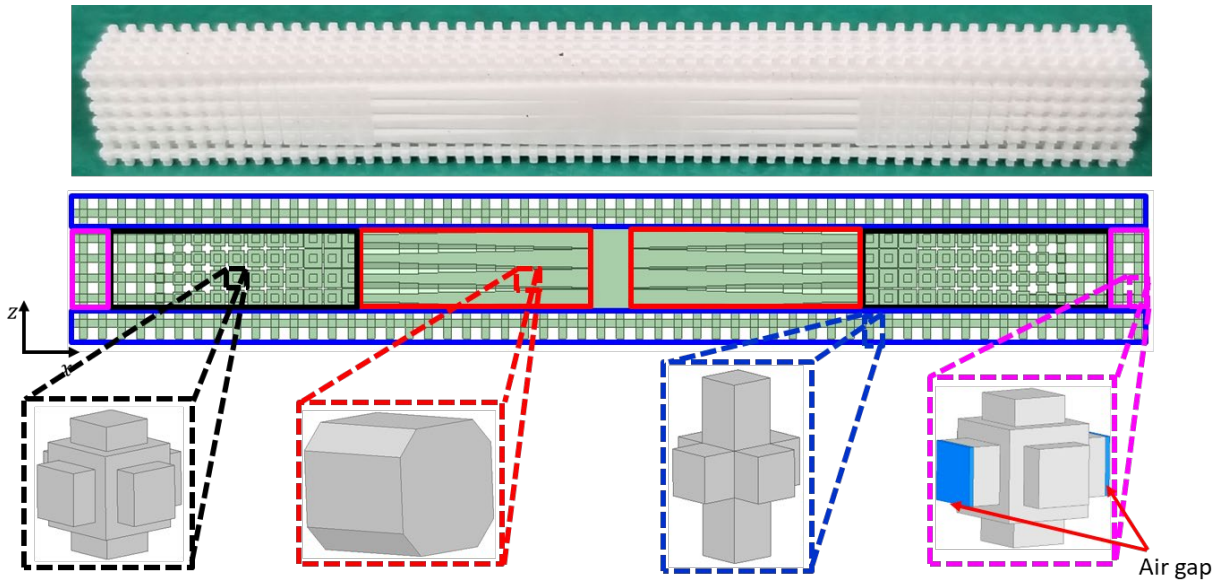

Figure 5: (top) 3D printed horn antenna lens with (bottom) unit cells designed by the UG student.

4) Code modulated embedded test

One student investigated a method for phased array calibration called code modulated embedded test (CoMET). In this method orthogonal codes are encoded into I and Q components of each antenna in an array using phase-shifters. The modulated signals are combined and squared through a power-detector. Interference from squaring creates baseband correlations which are then decoded, and amplitude and phase information is extracted. The student studied the CoMET approach and developed new codes to improve the calibration procedure. Codes were tested on an 8 element array and further testing was postponed due to university shut down.

Three students continued in an ECE graduate degree program at NC State and one continued to a graduate program at Cornell University.

C. Activity 3: Electronic Warfare Systems course

As part of this project, the PIs developed and offered a course on Electronic Warfare System during the Spring 2020 semester. The course was offered as a special topics course for both seniors and graduate students in ECE. Seven students enrolled for the course, six US citizens (including two ROTC students) and one South Korean army officer pursuing a Master's degree. All new course material was developed covering electromagnetics, propagation, antennas, RF circuits, radar, electronic attack, protect, and support. The course was taught as a 3-hour lecture/discussion once per week on Fridays. At the end of the course, students created presentations describing specific aspects of electronic warfare systems. A Zoom recording of these project presentations can be

viewed online[4]. Guest speakers during the semester included US Army Maj. Gen. Nickolas Justice, Prof. John Muth (former US Navy Commander), Capt. Andrew Hertel (Triangle Naval ROTC Commander), and Dr. Aaron Walker (CTO Vadum Inc).

Outcomes: Electronic Warfare Systems course

During the middle of Spring 2020 semester, campus was shut down and shifted to a virtual format, making this semester a little unusual. However, the EW Systems course was still a successful first offering of a course based on student feedback. Although traditional numerical teaching evaluations were not collected in Spring 2020, students' anonymous comments were very positive:

> *"This course was absolutely my favorite EE course in college. The real-world application and implementation of EW principles was a perspective like none other, truly. This course helped prepare me for my future more than any other course in my degree program. The material was perfect, the professors were amazing, the guest speakers were fantastic. Thank you for making this possible."*
>
> *"[the guest speaker panel] brought in very interesting perspectives in the EW space and was beneficial to students"*
>
> *"Overall, this was a very beneficial course and could benefit from a modules-based online format, or modules before a big one-day in-person seminar where hands-on studies are done. Please offer this class again."*
>
> *"I highly recommend this course to other students."*

Materials and relationships developed through offering this course have been used to create follow-on content for workshops and other events.

A. Activity 4: Radar Senior Design Project

In Fall 2019 and Spring 2020, PI Adams proposed a senior design project with the goal "Propose an experimental setup that demonstrates the properties of a radar system in a practical application and provide educational material to explain it" (following a prompt from the 2020 IEEE Antennas and Propagation Society Student Design Contest). PI Adams mentored the four student team, providing discussion and resources on radar systems. The team selected at 24 GHz FMCW radar board from Infineon and learned about how radar worked in order to implement various detection algorithms and study experimental cases. Unfortunately, like most coursework in Spring 2020, the system was only partially completed due to the university shutdown.

[4] https://drive.google.com/file/d/1ojQ05SXWzBsT-NwtGN9zOeBOs3LgAA3g/view?usp=sharing

Outcomes: Radar Senior Design Project

The four UG students learned about radar and signal processing and built a functional algorithm for detecting range, speed, and angular position of a metallic scatterer with an Infineon 24 GHz radar system. A schematic of their completed system is shown in Fig. 6 below. After data was measured, it was to be converted into sound to demonstrate radar functionality to a layperson, though only a crude functionality of this kind was completed at the end of the semester. Although the PI does not receive an evaluation as technical mentor, the students learned a significant amount about radar and will have a new perspective as they enter the workforce.

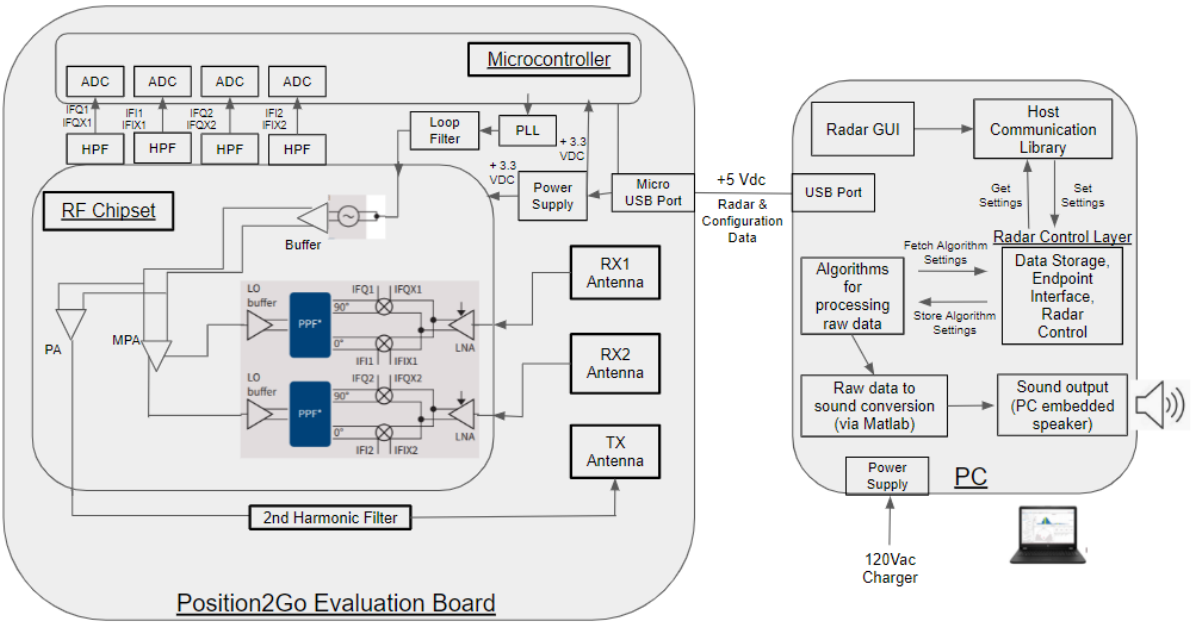

Figure 6: NC State Senior Design Team Radar System

What opportunities for training and professional development did the project provide?

The program offered numerous training opportunities to students – students worked as undergraduate researchers, took a special course offering on EW, worked on a senior design project to build and measure a radar system, or participated in the summer workshops. These opportunities are described in more detail in the section above. Overall, the project provided training opportunities for more than 60 US undergraduate students.

How were the results disseminated to communities of interest?

The program was described to stakeholders at ONR, NRL, NIWC-Pacific, and NSWCDD. In some cases, connections between students and these organizations were made to try to move students into an internship or other employment opportunities.

What honors or awards were received under this project in this reporting period?

PIs Ricketts and Adams were awarded the William F. Lane Outstanding Teacher Award in 2021 and 2022, respectively, in part for their work related to this program. The Lane Teaching Award recognizes excellence in teaching or educational leadership of one faculty member in the NC State Department of Electrical and Computer Engineering each year.

Technology Transfer

While there were no technologies developed under this award, the PIs have interacted with scientists and engineers at NRL, NIWC-Pacific regarding their recruiting needs and available hiring programs. We also provided a platform for these organizations to talk about their work to our undergraduate students, which benefits both students as well as the organization's visibility. We also developed a good working relationship with Capt. Andrew Hertel, Commander of the North Carolina Piedmont Region Consortium NROTC, who has repeatedly provided highly informative perspective to our students about EW in the field.

Participants

1. Type: Most senior project role
   Faculty
2. Prof. Jacob Adams
3. Number of person-months worked
   a. 1 mo.
4. National Academy Member? (Y/N)
   a. N
5. Country(ies) of international travel and duration of stay.
   a. Canada – 4 days

1. Type: Most senior project role
   Faculty
2. Prof. David Ricketts
3. Number of person-months worked
   a. 1 mo.
4. National Academy Member? (Y/N)
   a. N

1. Type: Most senior project role
   Faculty
2. Prof. Michael Steer
3. Number of person-months worked
   a. < 1 mo.
4. National Academy Member? (Y/N)
   a. N

5. Type: Most senior project role
   Faculty
6. Dr. Jordan Besnoff
7. Number of person-months worked
   a. 1 mo.
8. National Academy Member? (Y/N)
   a. N

Students

Number of undergraduate and graduate STEM participants
UG – 67 across all activities
Grad – 7 (including some who participated both as UGs and Grads)

Number of participants that received a STEM degree
UG – approx. 18 (the 45+ workshop participants were not tracked for graduation following the event)
Grad - 6