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ENGR497 – An Introduction to Research Methods Course

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Abstract

The benefits to students who engage in undergraduate engineering research are significant. Not only can students apply and extend knowledge they have learned in the classroom, they have an opportunity to engage in creative, abstract and critical thinking that leads to concrete, hands-on engineering applications. However, in many engineering programs, the current demand for undergraduate research exceeds available resources. As a result, many engineering students are precluded from participating in research during their undergraduate studies. Furthermore, most students enter research labs without the tools and background to hit the ground running. In this paper, we describe an inquiry-based engineering methods course designed to engage junior and senior level engineering students in structured, self-directed research at our university. This course is intended to stimulate creative engineering thinking in students while leading them through the process of conceptualizing and performing hands-on engineering research in a classroom setting. The course is open to all engineering undergraduate students and it is aimed at the development of student research skills and student preparation to perform mentored undergraduate research, therefore setting the stage for a more competitive and successful path to postgraduate studies or R&D industry career. In addition, this course helps close the gap between student demand for an undergraduate research experience and the often limited number of faculty-mentored research projects available to undergraduate students in engineering.

Introduction

Research is an important component of many engineering students' undergraduate education and it is generally believed to enhance the student's interest in pursuing graduate education and marketability in their chosen profession[1]. Undergraduate research experiences are usually mentored by individual faculty and are highly dependent on the availability of space and ongoing projects in faculty research laboratories that may be suitable to undergraduate student participation. With increased engineering enrollment at many universities and colleges, including ours, the availability of undergraduate research opportunities within individual faculty research laboratories can become a limiting factor in placing all undergraduate engineering students that seek to have a research experience. Moreover, the inherent variability in experiences across laboratories means that students are exposed to varying levels of structured learning during their research experiences.

Many research universities in the United States offer courses teaching research methods and techniques to students, but few of these are in an engineering environment. Furthermore, many of these courses are designed to teach students methods specific to a domain, design experiments to address a pre-defined problem, implement existing protocols, or perform literature reviews and develop proposals[2, 3, 4]. These are all very important components of the research process and enabling students to perform research in a laboratory. Here at Illinois Institute of Technology, under the umbrella of a Distinctive Education Initiative within the Armour College of Engineering, we challenged ourselves to build on these more traditional mechanisms for exposing students to research in a manner that would: 1) increase the opportunity for inquiry-based learning and creative engineering thinking; 2) prepare students for subsequent placement in a research laboratory; and 3) provide *all* engineering students at our institution an opportunity to perform mentored, self-directed research. Furthermore, as an engineering college within our university, we also felt that our solution should address the Engineering Accreditation Commission of ABET General Criterion 3, Student Outcomes, particularly student outcome b, "an ability to design and conduct experiments, as well as to analyze and interpret data"[5].

This challenge led us to develop an engineering-wide research course which exposes students to the research process in a structured, step-by-step manner. The main difference between this course and a more traditional approach is that the research topic is initiated by the student with the assistance of the class instructors. The student then performs each step of the research process using their chosen topic. Because the student will have an inherent interest in the problem they choose to solve, we anticipate the student will be exposed to a semester of significant inquiry-based deep learning, beyond what the student may achieve performing these same steps on a pre-defined problem.

The course begins with ideation in which students develop their research hypothesis. Next, students are led through a structured process to design and implement their research to test their hypothesis. At the end of the semester, students submit their findings to our university's undergraduate research journal and participate in our undergraduate engineering research exposition. Students may work alone or in small teams during the semester according to their research interests and preferences.

We believe that this method of teaching research, in which students apply their knowledge and techniques at a small scale, prepares students for future, larger research projects. At a fundamental level, students have the opportunity to explore research in their field of interest and developed a general sense of whether they would like to pursue research further in their career. With a focus in many universities on providing more research experience for students, providing a structured yet creative research methods experience expands the availability of research experience to a greater number of students. Here, we detail the development and initial findings of an inquiry-based, engineering-wide undergraduate research course.

Methods

The Course

We developed the course content and syllabus by obtaining input from a number of research faculty in our engineering departments to ensure that the course broadly meets the needs and expectations across engineering disciplines. An ABET-style syllabus was also developed to identify the student outcomes for the course and to help each engineering department understand how they could use the course to support student outcomes a-k (Appendix). This course provided broad coverage of many ABET student outcomes since we included topics such as engineering and research ethics and communicating research findings, in addition to the research process itself. The course is open to all engineering students and does not have prerequisites; however, it is a 400-level course, and therefore only students who have completed the majority of their core courses are able to incorporate the course into their schedules.

The research methods course includes both lecture and laboratory work each week during the semester. During the first two weeks of the course, students explore potential topics for research and define their teams (or work individually). Some students come to class with a topic already in mind while others find this part of the course very challenging. The course instructors work closely with the students to address student differences in initial starting point and discipline background and engage all students in a productive learning experience.

A week is dedicated to literature review. Students are guided through the literature review process by our engineering librarian, then conduct a literature review on their topic of research. Once the literature review is completed, time is spent with each team making sure the proper question or hypothesis is generated. Next, a high level research plan is developed with a corresponding list of equipment and materials that each student needs in order to perform their experimentation. Students are allowed to purchase small items needed for their research if the items are not available in the currently existing undergraduate research lab. We do not have a set budget for the students because we might decide to spend more on a particular item because of its reusability for future experiments. Consumables average approximately $80 per group. Because of the lead time on certain items, we have found that we must take students through the ideation, literature review and research planning process quickly. Lab safety issues are covered before the students begin any experimentation.

Once the initial planning step is complete, students begin learning fundamentals of data collection and analysis. Statistical concepts on data collection, including the use of Matlab, and Design of Experiments are covered. As students learn these concepts, they are expected to apply them to their research plan. Arduino sensors are used as a means to easily collect data within different experimental setups. Students are introduced to a variety of sensors available for use with Arduinos and are expected to make use of these tools in their investigation. During the lecture periods, students are also required to complete specific assignments that may not directly relate to their research, but are for the purpose of reinforcing the lecture concepts covered.

These steps usually take the first third of the course, at which point students are now prepared to fully dive into their research project for the second third of the course. Students now spend most of their time in the laboratory and are expected to make significant progress executing their research plan. A session on ethics in research is also reserved for this class during the middle of the semester.

The final third of the course is dedicated to helping students complete their research, analyze data and draw conclusions. Students are instructed on reporting their findings in a research article, which is submitted to our university's undergraduate research journal for publication. Students also prepare a poster on their research findings which they present at our undergraduate engineering research exposition, held every semester. Finally, students are also instructed on developing proposals to continue their research, and are encouraged to apply for competitive undergraduate research opportunities available on campus through the college of engineering undergraduate research program.

The Laboratory

The setting for this course is a newly opened undergraduate research lab with the sole purpose of enabling students to independently conduct research at the undergraduate level (Figure 1). This lab is unique in that it is open to all engineering undergraduate students at our university who wish to perform research on their own or within a group. There is no requirement for the student to be working with a professor.

The lab is the size of a typical faculty research laboratory in our institution with wall benchtops and cabinetry, a large center benchtop, distilled and deionized water systems, and two fume hoods. The lab is equipped with basic lab equipment (such as load cells, calipers, pipettes, and temperature measuring devices), specialized equipment (such as a scanning spectrophotometer and a bomb calorimeter), and an extensive array of Arduino sensors and shields The laboratory lends itself well for the purpose of teaching an introduction to research course. The space is divided into various sections to foster research in four thematic areas: water, security, health and energy. These four Engineering Themes were identified as having substantial societal and scientific relevance and provide both curricular and extracurricular enrichment of the educational experience for our engineering students. Much of the laboratory equipment was purchased specifically to support research within these themes.

Figure 1. Research laboratory dedicated to engineering-wide self-directed undergraduate research.

Results

The course has now been offered three times since its inception. The first time the course was offered, it was piloted with students participating in faculty-mentored undergraduate summer research through the Armour College of Engineering Program for Undergraduate Research Education[6]. These students were ideal for this class, as they clearly had an interest in performing research.

In the pilot course, students participated by forming teams and pursuing small research projects distinct from their faculty-mentored research. Piloting the course in this manner allowed us to fine tune our lectures and adjust the scope based on feedback from students during the course. This initial test run highlighted the need for a small budget for each research project to allow students to purchase equipment for their experiments. We also learned that the summer semester is not the best time to offer this course, due to the limited time during which a small research project can be completed within a given credit hour setting, typically 6-8 weeks.

Our pilot group was very keen at giving advice on how to improve the course and providing insights into their learning experience. We had two major takeaways from this pilot regarding course content, based on written student course evaluations. One, students particularly appreciated the time spent on lecture topics, and many requested more time allocated to these topics: “The lecture material was very useful and gave great insight into how to do research better”; “…more lecture material possibly regarding presentations and data analysis”; and “I would increase some focus on data analysis, computational tools, and software methods”[7]. Two, what makes this course truly unique – the opportunity for students to pursue their own research ideas – was one of the top responses when students were asked what they liked most about the course: “The practical experience and the freedom to pick our own project for the lab”; “I think proposing our own project is what makes this class wonderful”; “I liked how it was open-ended and we had an opportunity to be creative and figure out experiments on our own”; and “I liked the freedom to choose my own projects. I have a bunch of ideas that I would love to utilize the resources in the lab for[7].”

The second time the course was offered was also the first time students took the course officially for credit. The class size was very small, with only three students. This turned out to be ideal for us as we could further fine-tune and expand the course into a full semester. We also incorporated our learnings from the summer pilot course and developed enhanced data collection and analysis course modules that included Matlab and Arduino instruction. Three compelling research projects were successfully completed, with each student researcher following the same structured process. The three research projects were: 1) Green Walls and Energy Savings Analysis; 2) Design and Testing of a Modular Camera; and 3) Analysis of a Renewable Energy Floor. Each student wrote a final paper in formal publication format and created a poster to present during the engineering college’s research day expo (Figure 2). Based on feedback, students clearly believed they developed knowledge and skills to help them be successful in future research and gained an advantage over other students in securing future research positions. Two of the students went on to pursue research over the summer with faculty members in their respective departments and the third student pursued an internship.

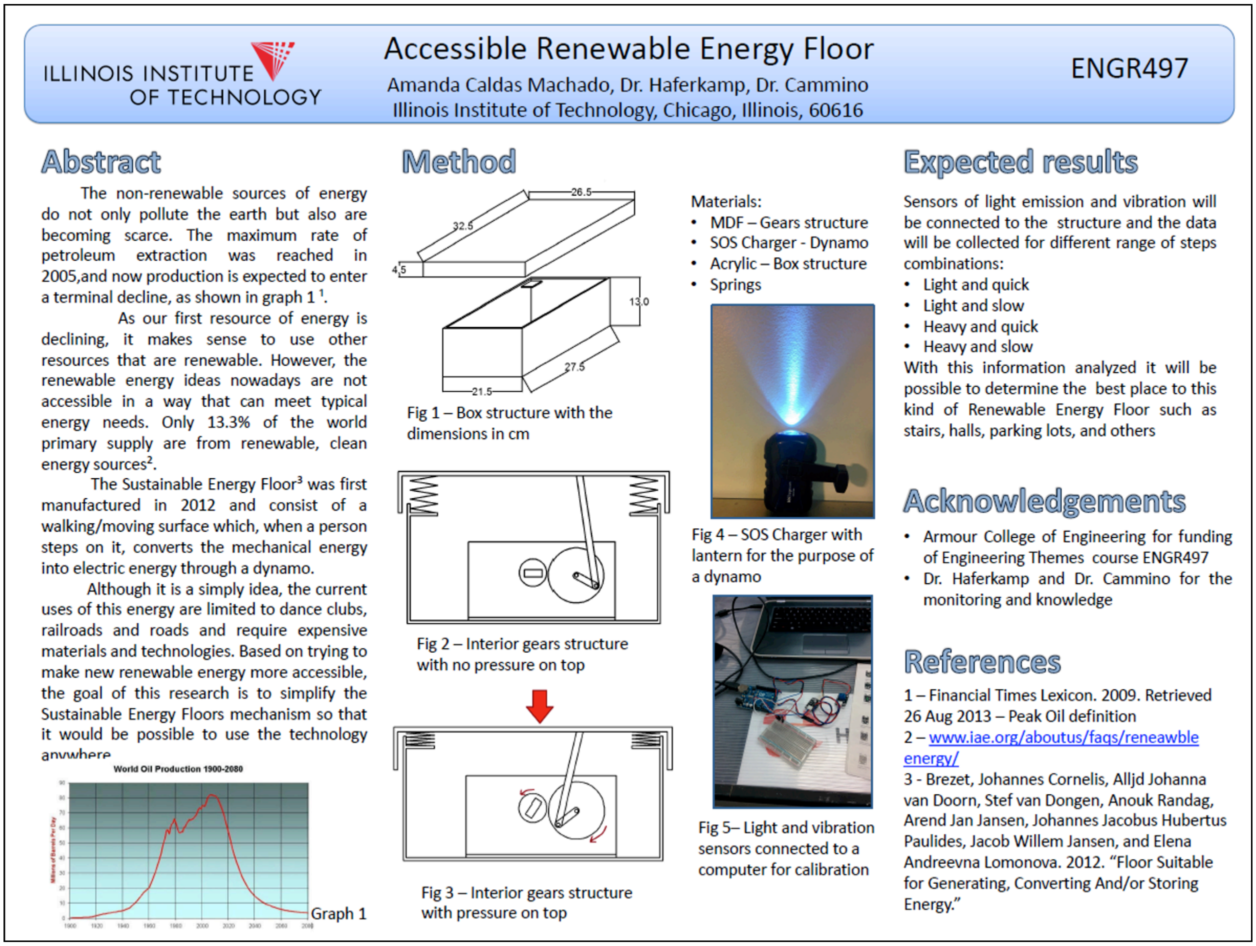

Figure 2. Student poster presented during our engineering-wide research day expo.

We are now offering the class for the third time in the last 1.5 years and have achieved an enrollment of 15 students. We believe this is the right class size for this type of activity. In this case, we now have teams of 2-3 students each, with some students pursuing individual research. We have discovered that this course can also be very attractive to master's degree students who are either pursing a Master of Science or a Professional Masters. Students pursuing a Master of Science will have an opportunity to become prepared to pursue research for their thesis, while Professional Masters students can gain exposure to research, while still maintaining the flexibility afforded by a non-thesis, professional master's program.

Sample projects from the latest offering of the course during the Spring 2015 semester cover diverse topics, such as composite modeling of sports equipment, security of Arduino wireless signals, water quality testing on various sources of captured snow melt, and fermentation for cellulose production. We continue to expand the capabilities of the laboratory by purchasing additional equipment and materials as the course grows in popularity and to support the wide range of research topics that students wish to pursue.

Evaluation and Assessment

Student evaluation in this class is based on the fulfillment of all assignments, including the final research paper and poster. Students are evaluated on concept-reinforcing assignments, particularly during the first third of the class. Their research progress is monitored throughout to ensure that students are putting in the appropriate time and effort necessary to successfully complete their research. Students must successfully complete a journal-style final research paper and research poster in order to pass the course.

Homework assignments are designed so that students can easily incorporate the material covered in lectures directly into their research. We have developed tighter integration between lecture material, homework assignments, and the student research projects each semester in an effort to increase student learning. For example, the first time the course was offered, the Design of Experiments lectures were followed by a generic assignment with a small scope. Approximately half of the students failed to translate this concept rigorously into their experiments. We now teach an expanded lecture on Design of Experiments in which students are assigned the task to create a Design of Experiments as it relates to their research. Students also completed their assignment over a longer period of time. Because students often initially conceptualize their experiments with a large number of variables, with the expanded Design of Experiments coverage, they quickly realize they need to rethink the scope, controls and variables within their experimental plan in order to design a manageable experiment. With these changes, we now have almost 100% of the students able to rigorously apply Design of Experiments to their experimental plan.

Similarly, the section on data analysis originally required a generic homework assignment and assumed some level of Matlab programming. We found that students enjoyed learning to program microcontrollers and collect sensor data, but had difficulty with sensor calibration and data analysis using Matlab. This section of the course is now taught first with an overview of the principles and a demonstration, followed by hands-on lectures with data collection, data filtering and sensor calibration, and additional basic training on Matlab. We now have almost 100% of the students able to identify and calibrate the appropriate sensors for their projects, and appropriately collect and analyze data.

A major component of the course objectives evaluation occurs during the college's research day expo. This was not an original requirement of the course, but was incorporated into the course so that we could evaluate our students side-by-side with undergraduate engineering students performing traditional research in faculty-mentored laboratories. The posters are evaluated by several judges as well as the instructors for the course. We use the objective feedback from external judges to assess the course effectiveness and modify course content accordingly. Beginning this semester, we will also be adding additional quantitative indirect assessment using student questionnaires, and follow students after the course completes to determine the extent to which the course impacts the students' perceptions of and ability to perform research.

Discussion

Our goals in creating an engineering research course were to enhance research-based deep learning opportunities for students that would also prepare them for subsequent faculty-mentored research, and to make hands-on research available to all engineering students in our university. We believe that the current implementation of this course is achieving these goals. This is due in part to several elements of the course that were defined prior to the course implementation:

1. **Student-initiated research.** Because the research hypotheses are defined by the students, the students have an inherent interest in the topic. This seems to be a crucial step in making this class different from any other course and engaging the students. An interesting learning outcome from this approach is that many students easily identify research topics of their own and truly take ownership for their research success. This facilitates the overall class and enhances the student experience. This would not be the case if there were, instead, prescribed research topics for the students.

2. **Laboratory space and equipment dedicated to the course.** It is extremely important to have a dedicated space for students to conduct their research, rather than at scattered locations around the campus. The dedicated lab space allowed this course to be a success. Naturally, some of the research was conducted outside of the dedicated lab space and utilized other campus resources, but providing a common meeting place for students to conduct research together on different topics enhanced the class experience. Students can learn from each other as they struggle through roadblocks in their research and help each other find solutions.

3. **Rigorous, structured approach to the research process.** This course was designed to provide structured learning, inclusive of homework assignments and milestones to be achieved during research. Students apply their lecture learnings to their own research ideas, providing for deep learning opportunities[7]. This approach ensures that students retain an understanding of the research process beyond the course, and receive proper credit for the course from the college and the accreditation board.

4. **Integration with other Distinctive Education programs.** The engineering methods course is part of a comprehensive program offering a distinctive educational experience for engineering students. This course directly benefits students by helping them develop their research skills and thinking. However, as part of the Distinctive Education program, students can immediately apply and solidify their learnings from the course in other Distinctive Education programs, such as the Armour College of Engineering Program for Undergraduate Research Education[6], and document their participation in the Armour College of Engineering online portfolio[8].

We piloted this course as a non-credit course for students participating in faculty-mentored summer research. As a result of the pilot and subsequent full semester implementation, we believe it could be useful in the future to make this course available using two options: one with the lecture portion only and one with the lab and lecture. The lecture-only option would be equivalent to a 2-credit hour class, targeting students already involved in undergraduate research on campus. This would allow students to learn research methods in a structured manner and apply them to their faculty-mentored research project. This would also work well for beginning Master of Science students. The second option is a 3-credit hour course available to students who are not participating in faculty-mentored undergraduate research.

The demand for undergraduate research opportunities outstrip faculty-mentored capacity; thus a course of this nature allows more students to be exposed to research than can typically be handled within a traditional university setting. This course can complement summer research activities, relieving the students' research advisors from this task. However, one issue that arises is the additional cost of tuition for students. Summer courses are an additional expense at our university and invariably the most common time for students to be involved in research programs. One way to successfully incorporate this course in a summer research setting is to offer students faulty-mentored research opportunities which include a stipend as well as a tuition voucher for the lecture portion of the class. This would relieve the financial burden on the students. We have not explored the lecture only option during the traditional fall and spring semesters, primarily because students involved in research during the regular semesters have a full course load and difficulty incorporating a 2-credit elective course. Most of our engineering curriculums are based on 3-credit elective courses, making it challenging for students to justify taking a 2-credit hour elective. We continue to explore means to make this course more available to students and at different credit hour levels in order to benefit a greater number of students.

During the course development and implementation, we identified an important yet unanticipated factor that influenced our success with the course. This course is taught by two engineering faculty members from different engineering departments. This allowed us to provide broader coverage of engineering domain knowledge than if the courses had one instructor, or instructors with similar scholarly background and areas of expertise. Since students enroll from all engineering disciplines, this broad coverage helped to provide better support for the students in the course, particular during the ideation and experimental design processes. We were fortunate that this course was conceived of and implemented at a college-wide level as part of a greater program to enhance engineering education, as many of the benefits of a college-wide engineering course are simply not possible within a course implemented by an individual department.

To provide insight into the students' perspective, here is a set of quotes from our most recent students who have taken this course[8].

"I took the ENGR 497 course because I was interested in doing undergraduate research. The most important thing I gained was the ability to know how to approach research. The process I believe is very important because it can be applied to any field and to any subject matter. The one thing I would of liked to see different is helping the students in the class come up with ideas for research. For example, work with professors in their department who are doing research the student might be interested in and have those same professors suggest research projects that would work under the construct of a semester class. This could potentially lead to the student doing further research with the same professor in the future. The class mainly helped my future by giving me important skills that can be translated to industry, such as design of experiments and stochastic analysis, and by preparing me for the most important aspect of graduate school, research, when I choose to pursue a master's degree in the near future." From G.C. – ME major 2015

"I signed up for ENGR 497 because I wanted formal training as a researcher. My short term goal is to become a Ph.D. candidate and be funded as a Research Assistant.

The course was a valuable learning experience for me and it helped me grow as an independent researcher.

On a separate note, our Professor's story of how she switched from working in industry to doing research in academia was inspirational." From G.K. –ME and MS major 2015.

Acknowledgements

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Appendix A. ABET-style Syllabus

ENGR 497 – Introduction to Research Methods

Credit Hours: 3.0

Contact Hours: 1.5 lecture hours/week and 3.0 laboratory hours/week

Instructor: Roberto Cammino and Bonnie Haferkamp

Textbook and Other Materials:

None required. Safety goggles and a laboratory notebook are provided.

Catalog Description: This course introduces students to research methods and contemporary issues related to research in a university setting. Students will be introduced to research proposal development, scientific literature reviews, measurement techniques, statistical data analysis, design of experiments, good laboratory practice, and oral and written research communication. Ethics and intellectual property topics related to research will also be covered. During this course, students will be involved in hands-on experimentation in order to practice their measurement and data analysis skills as well as test their hypotheses. Experiments will focus on the Engineering Themes of Energy, Water, Health and Security.

Prerequisites: None

ENGR 497 is an elective course for all engineering curriculums and an engineering elective for BME and CHBE

Course Outcomes:

1. The student will be able to maintain a laboratory notebook of their experimental data and findings
2. The student will be able to perform a literature review to support research planning.
3. The student will be able to apply Design of Experiments to their research planning.
4. The student will be able to apply statistical data analysis to experimental data and draw conclusions.
5. The student will be able to evaluate engineering ethical considerations to their research and to case studies.
6. The student will be able to research, plan, execute and evaluate a self-defined research project.
7. The student will be able to evaluate the broad impact of their engineering research and relevant constraints.
8. The student will be able to communicate their research plans and findings orally.
9. The student will be able to prepare a publication-style research paper on their research performed in the course.

Student Outcomes:

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 identify, formulate, and solve engineering problems
d) an understanding of professional and ethical responsibility
e) an ability to communicate effectively
f) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
j) a knowledge of contemporary issues
k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

Topics covered in this course:

- Background research for experimental planning
- Design of Experiments
- Statistical data analysis
- Executing engineering experiments and analyzing experimental findings
- Oral communication of research
- Written communication of research
- Engineering ethics
- Intellectual property, social impact, and financial considerations of engineering research
- Software and hardware tools, such as Matlab, LabView, Arduino, etc. (student-specific)
- Laboratory safety
- Laboratory notebook maintenance

Appendix B. Course Schedule

Week 1

- Students will select a Topic of Research and either form research teams or decide to work individually. Students will begin creating a research plan. Students will be provided laboratory safety training.
- Students will be provided with a laboratory notebook and instructed on proper use of the laboratory notebook to record their experimental data and findings.

Week 2

- Students will be introduced to Literature Review and Library Research techniques.
- Assignment 1: Students will be individually assigned to perform a thorough literature review related to their topic of research. Each student will submit his/her own findings. As a team, students will create a literature review summary for their research work.

Week 3

- Students will be introduced to Statistical Data Analysis and Design of Experiments Techniques.
- Students will continue their research.
- Assignment 2: Students will be individually assigned the task to prepare a potential statistical analysis to be carried out during their research. As a team, they will agree on a data analysis plan.

Week 4

- Students will continue to learn about Statistical Data Analysis and Design of Experiments Techniques.
- Students will continue their research.

Week 5

- Students will begin applying their learnings on Statistical Data Analysis and Design of Experiments Techniques.
- Students will continue their research.
- Assignment 3: Students will be individually assigned the task to prepare potential Design of Experiments to be carried out during their research. As a team, they will agree on a Design of Experiments plan and execute it.

Week 6

- *Ethics in Research Workshop*. Students will participate in a workshop in which they learn about ethics within engineering and research. Ethics rubrics and case studies will be discussed.
- Assignment 4: Students will be asked to summarize and determine what ethical concerns there might be with their research. Students will also explore financial and social impacts of their work.

Week 7

- Students will continue their research and experimentation.

Weeks 8,9,10

- *Data Acquisition & Analysis and Sensor Calibration.* During this time, students will learn about sensors and real-time data acquisition using Arduino-based systems. Sensor calibration, data analysis and filtering techniques using Matlab will also be covered.
- Students will also continue on their research at this time, by incorporating their sensors learnings, within their project.
- Assignments 5 & 6: Students will identify sensor needs in their projects, calibrate the sensors using Matlab, acquire data, and apply filtering and analysis techniques appropriate to their sensor/research project.

Week 11 & 12

- Students will be instructed on communicating research findings through a journal-style publication and a poster.
- Students will continue their research.
- Assignment 7 & 8: Students will develop a journal-style paper to submit to the student research journal and a poster to present their experimental findings at the student expo.

Weeks 13

- Students will continue to complete their research.
- Students will receive individual support for their journal-style paper and poster.

Weeks 14

- Students will continue to complete their research.
- Students will receive individual support for their journal-style paper and poster.

Weeks 15 and 16

- Preparing research proposals.
- Posters completed and presented at the undergraduate expo day.
- Papers completed and submitted to the undergraduate research journal.