Paper ID #36555

Building/Testing Novel Sensor Technology in Summer Research & Independent Study

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Abstract

Practical learning is an inherent part of the engineering curriculum. Engineering students best learn the course material through intensive hands-on experiences. Research and independent study opportunities allow students to directly apply their engineering knowledge to real-world problems as a continuation of their in-class learning. The research and independent study opportunities under the guidance of an ECE professor described in this paper have provided students with unique experiences to augment their coursework with diverse applications as well as increasing agency in their developing engineering careers. Agency in education allows students to create rather than seek out learning opportunities. The students can also get practice with innovative problem-solving — promoting innovative thinking is crucial to develop as an adaptive expert. One proposed adaptive expertise framework differentiates two dimensions a learner may develop: efficiency and innovation. Undergraduate education focuses on widening the breadth of the content a student is exposed to – an expert, in a classical sense, is defined as being efficient when solving routine problems. On the other hand, an adaptive expert can innovate when faced with problems that are not routine. The latter is the product of incorporating student-centric learning into the undergraduate curriculum – providing future experts with the innovative space to foster their professional and personal skills to become better practising engineers. The learners are challenged through open-ended design problems as the work is often student-led. These experiences provide practical skills, but they are also essential in building professional skills such as teamwork, leadership, troubleshooting, and best design practices. This paper describes our recent efforts to provide more adaptive learning experiences via building and testing a novel Mach effect sensor technology over the past few years in summer research and independent study opportunities at Bucknell University in the College of Engineering. Herein we provide information about the novel sensor system that the students worked on / and enhanced through their independent study courses and summer research experiences since 2019. The specific technological updates to the novel sensor device will also be discussed. This work should be of interest to engineering faculty and students as it demonstrates the important role independent study and summer research can play in enhancing and deepening engineering education as well as faculty research initiatives.

Keywords

Independent study; undergraduate research; research fellowships; Mach effect; novel sensor

Introduction

Most institutions offer independent study courses and summer research to allow students to work closely with faculty members while pursuing their topic of interest. Independent study projects are often designed for students who demonstrate the ability to work independently on open-ended or research-oriented projects. These opportunities are innately different from the structured, professor-led courses – they foster agency and creativity and closely mimic the autonomous work environment students will face in their chosen profession. In contrast to contemporary undergraduate learning approaches, engineering research allows students to pursue a scientific topic or hypothesis rigorously – creating new knowledge in the process. The agency that the students develop contributes to a lifelong skill of independent scientific thinking. This unique aspect of engineering education is typically not a significant part of most engineering core curricula; therefore, many students may go through their entire undergraduate education without a genuine research experience. Many industrial environments require some level of engineering research. Hence, independent study and research could be opportunities to explore for improvement of the ECE curriculum. These experiences provide an invaluable glimpse of life as a practising engineer.

In earlier studies[1], undergraduate independent study experiences were described as high-impact practices due to their capacity for active student engagement and opportunities for students to work with cutting-edge technology, answer prominent scientific questions, and create new knowledge. These opportunities involve a more frequent and personalised relationship between the faculty and student with a strong emphasis on mentorship practices. The role of faculty members in independent study is more similar to a project advisor or a source. Faculty members act as clients with specific directions for the project; a student is provided complete independence in the decision-making as long as the predetermined milestones and objectives are being met. The faculty's role is among the many similarities between independent study and undergraduate capstone experiences. Since the expectations of the faculty are different from regular courses, students have the opportunity to explore a scientific topic or hypothesis in-depth. This is in contrast to the constrained depth of material in other engineering courses. These constraints are in place to maximise the information that can be passed along in the time allocated for the course. Moreover, they provide clear expectations and accountability in the classroom. In most undergraduate engineering education, the grading system is clear-cut and outlined in the formal syllabus. It often considers homework assignments, projects, or exams as key contributors to the grading criteria. The grade essentially constitutes a contract between the professor and students. Without a contract, it is highly probable that these autonomous learning opportunities may inadvertently become a source of frustration and disappointment between the faculty and the student. The most common cause is usually a mismatch between the expectations – resulting in a poor allocation of student's time and resources. Therefore, the faculty and students must work together to set realistic objectives and expectations. This joint effort will maximise student productivity while, at the same time, giving them a clear idea of what is expected of them and where their efforts would be most impactful.

Research Project Progression

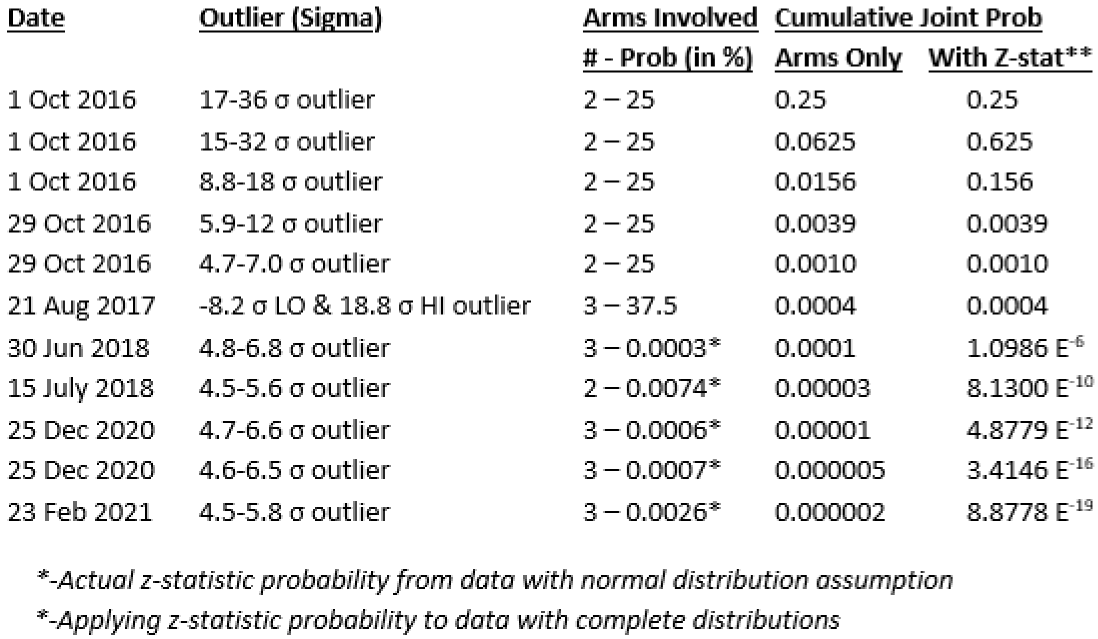
Over the past few years, over a dozen undergraduate students participated in the novel sensor research experience described in this paper and previous publications[2-7]. These research-based learning experiences span three summer internship teams and five separate independent study courses since 2019. The semester independent study and summer research teams were often composed of engineering students from multiple disciplines. The teams have the agency to choose the project objectives they want to achieve, particularly during the summer research period when their roles are typically defined predominantly by student research fellowship requirements governing their stipend award (see Appendix A). This allows the team members to self-motivate. Students work on separate subsystems – they're responsible for defining milestones to add or improve functionality of the system overall. The team members can make iterative design changes based on the characterisation and testing of the system. The students interacting with the system much more frequently can make recommendations to improve functionality, ease of use and accuracy. The overall goal of the research project at the time is developing and characterising version 4 of the novel sensor/detector system. Besides the mechanical improvements, the main advantage of this version is the automation capability. Measurements for versions 1 through 3 of the device were made manually and were not only very time consuming but in previous versions still had opportunity for there to be greater concern of possible human error in portions of the protocol that had yet to be automated. Our research team had received feedback from reviewers of our academic publications as well as other professionals which have kept us in a continuous improvement modality. To minimize these criticisms in the future as well as to eliminate as much opportunity for human error as possible, one of the core objectives for this research project in the past few years has been to minimise the human input into the system – in other words, this meant automating the ramp-up of the device, its associated runtime, system control along with the data acquisition for real-time battery voltages and inertial disc rotational velocity. One of the core reasons this work is so critical is that the results achieved to date by all of the previous teams indicate that this novel sensor may be detecting a here-to-fore unobserved connection between matter (manifesting as an electromagnetic interaction). The most recent data collection (Dec 2020 – Feb 2021) reported in [2] is using the version 3-a of the device. And the protocol for running the experiment and pre- and post- data collection is consistent with those previously reported for version 3 [3-7]. Table 1 shows a summary of the 11 anomalous experimental observations to date (18 "Hits" in Table 1 shows that often there were multiple targets on the impacted detector arm / battery) and the correlation of battery outliers with only 3 distinct masses. Table 2 summarizes our initial joint probability calculations that these novel correlations could have occurred purely by chance. We have assumed normality in the voltage discharge distributions, independence of our experiments,

Table 1 – Correlation of Outlier Observations to Known Celestial Masses

Mass	Detector Hits	Percentage of All Outliers
Sun	8	72.7%
Virgo Supercluster	7	63.6%
Milky Way Center	3	27.3%

etc. Data collected since 2018 (the last 5 observations in Table 2) represent the experimental work of multiple student undergraduate research teams at Bucknell. As one can imagine, removing all potential criticism of human error becomes imperative when we are reporting such seemingly impossible results and making such bold assertions of observation.

Table 2 – Initial Joint Probability Calculations



Date	Outlier (Sigma)	Arms Involved	Cumulative Joint Prob	
		# - Prob (in %)	Arms Only	With Z-stat**
1 Oct 2016	17-36 σ outlier	2 – 25	0.25	0.25
1 Oct 2016	15-32 σ outlier	2 – 25	0.0625	0.625
1 Oct 2016	8.8-18 σ outlier	2 – 25	0.0156	0.156
29 Oct 2016	5.9-12 σ outlier	2 – 25	0.0039	0.0039
29 Oct 2016	4.7-7.0 σ outlier	2 – 25	0.0010	0.0010
21 Aug 2017	-8.2 σ LO & 18.8 σ HI outlier	3 – 37.5	0.0004	0.0004
30 Jun 2018	4.8-6.8 σ outlier	3 – 0.0003*	0.0001	1.0986 E^{-6}
15 July 2018	4.5-5.6 σ outlier	2 – 0.0074*	0.00003	8.1300 E^{-10}
25 Dec 2020	4.7-6.6 σ outlier	3 – 0.0006*	0.00001	4.8779 E^{-12}
25 Dec 2020	4.6-6.5 σ outlier	3 – 0.0007*	0.000005	3.4146 E^{-16}
23 Feb 2021	4.5-5.8 σ outlier	3 – 0.0026*	0.000002	8.8778 E^{-19}

**-Actual z-statistic probability from data with normal distribution assumption*

**-Applying z-statistic probability to data with complete distributions*

The real-time data acquisition system was one of the first additions after the version 4 device was first manufactured. RPM measurement has been a challenging task since the device can rotate up to 9000 RPM in some instances. This proved to be a challenge to laser tachometers. The students proposed a Hall Effect sensor to perform this subtask as an alternative. This was an unconventional approach to the problem, but the new sensor made it possible to automate the task effortlessly with accurate monitoring of inertial disc RPM.

The redesign of the PCB boards from flex to rigid-flex was one example of the latter. The intended functionality of the PCBs, as specified by the client, was to attach forty-eight (48) batteries to the frame and support power flow to the DC motors which in turn provide the required torque to spin the central inertial disc of the device/sensor. However, even though the novel, flex PCBs were a serious upgrade to the device from the manually-interconnected battery holders of version 3, they created an unexpected reliability problem. The amount of stress (normal wear and tear) that these boards would experience from continual loading and unloading of the AA batteries was not accounted for in the design. This created the opportunity to update the boards from flex to rigid-flex. This provided a more suitable board for the specified function while also providing an opportunity for an undergraduate student to design an advanced rigid-flex printed circuit board. These types of experiences are distinct from those in regular engineering courses. It is essential to emphasise the value of developing independent scientific reasoning in young engineers. The students can be engaged in numerous ways to develop this characteristic. One such approach that has proven successful in the past two years was an active effort from the faculty member in charge – Dr. Jansson – to promote scientific discourse by allowing students to challenge all aspects of this research. By encouraging students to keep their scepticism, Dr Jansson encourages the students to work on disproving the significance of past research findings. This allows students to think freely as there are no wrong ideas as long as one can back them up with scientific data. The students learn to apply their course knowledge to make scientifically accurate assessments through this rigorous process. Moreover, they get to experience some aspects of academia. The students often have the opportunity to have their work included in academic publications. As an example, over six different undergraduates have published with our research team in just the past 3 years on this very topic. For an undergraduate, this is a rewarding but challenging task. Students undertake their respective tasks seriously as the agency in their work also holds them accountable for it. This develops a sense of ownership of the research project in the students – a glimpse into their future professional careers. The independent study and summer research experiences provided in this format are similar in many ways to experiences we seek to provide in our engineering capstone design course sequence. When the students are given agency, they can often produce their best work. They can apply creativity and explore unconventional approaches in their research and practice.

Research Project Ongoing Objectives

One of the notable student enhancements from version 3, 3-a to version 4 of the device is the use of the rigid-flexible printed circuits boards (PCBs) described earlier to eliminate wiring issues and reduce noise. An advantage of the novel PCBs is that they enable the real-time collection and analysis of each individual battery's voltage. Since each outlier observation is always an individual battery, this will give the research team greater insight into how the outlier manifests over time. This modification also eliminates the chance of human error when measuring and recording the pre- and post- voltages of the batteries which is needed to determine outliers. Each of the new, rigid-flex PCBs also has a shunt resistor that enables the measurement of the current flow in each of the sensor array (detector) arms for the very first time. This will be invaluable in assessing the reality of real time voltage swings vs. artefactual. The sensor leads for each arm of the device run to a dedicated MCC 113 Voltage Measurement DAQ HAT [8] for a Raspberry Pi® 3 (Model B) via a ribbon cable. Each arm of the novel sensor array is connected to the Raspberry Pi via stacking as shown in Figure 1.

Perhaps the most significant revision the team has undertaken in version 4 of the sensor array is the reduction in size of the spherical sensor grid surrounding the central inertia disk. We reduced the absolute spatial distance between sensors to become more like what was employed during the experiments in the winter of 2000. This achieves multiple goals including minimizing the departure from the initial system design while increasing the effective signal reception area of the sensor array (batteries) surrounding the central disk. Our calculations indicate that we have increased sensor area around the central inertia disk from ~1% in version 2, to ~8% in versions 3 and 3-a to ~25% in version 4. As shown in Figure 2 we have reduced the diameter of our sensor array sphere from 34.3cm (version 3) to 18.5cm in version 4. It operates with ceramic bearings, a streamlined central disk and laser alignment of its drive motors which all lead to lower power consumption. Work is ongoing to refine the protocol for the operation of this new device. We now have the ability to bring the device to a very high speed (the gyroscopic state) without an

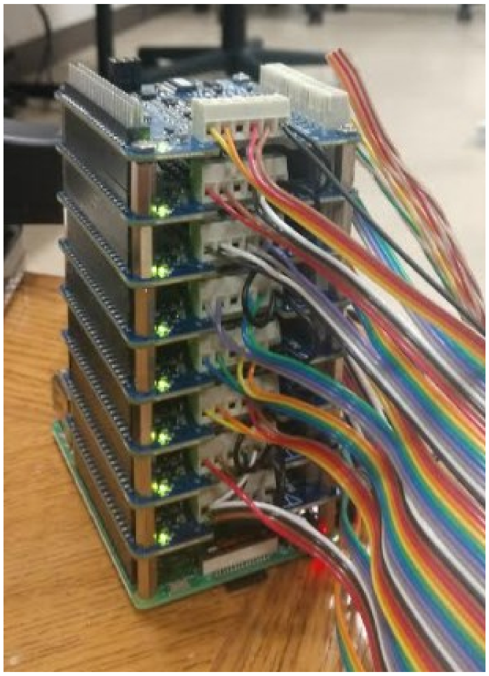


Fig. 1 – Raspberry Pi and Eight (8) MCC113 DAQ HAT Boards

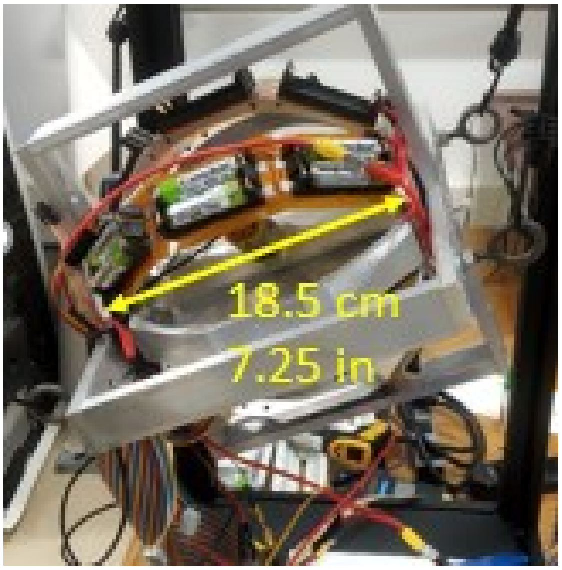


Fig. 2 – Mach Effect Sensor Array – Version 4

external DC power supply on battery power alone as shown in Figure 3. At that state our experience has shown it is more likely that these Mach Effect observations can be regularly made. As the device moves into greater refinement as a true scientific instrument / sensor array, we now can more fully automate its operation and control. The new version 4 will be controlled to allow for a gradual ramp-up of disk rotation (similar to the early experiments). Figure 4 shows our near-term challenge of controlling the current requirements as we ramp the system up gradually to assure the safety and long-term resilience of our rigid-flex PCB data acquisition and DC power flow system. Most importantly, based on the work of our most recent summer student research team we are now able to better document and characterize all energy going into the system and performance of the device over time for the entire duration of each experimental run.

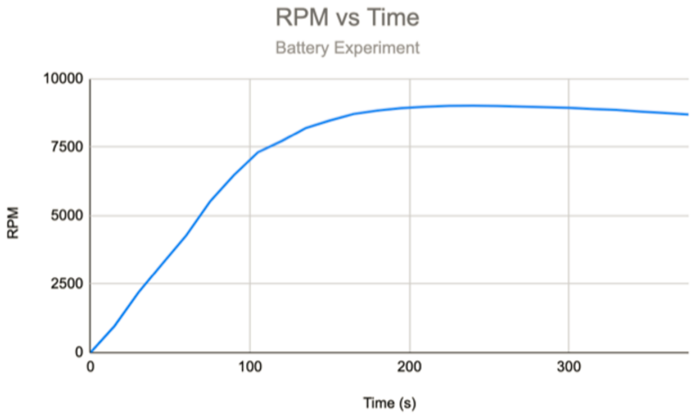


Fig. 3 – Rotational Characterization – Version 4

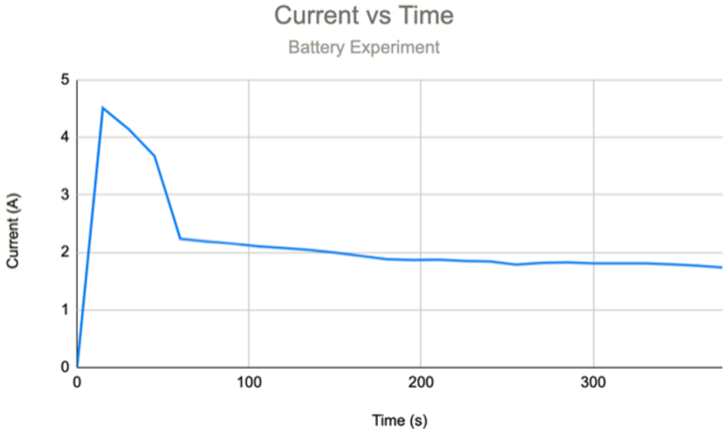


Fig. 4 – Current Characterization – Version 4

As our student research team further automates the new version 4 we will also be for the first time able to document all of the power flows through the system (by arm) for typical control runs and create a significant amount of statistical information for normal behaviour. We will also be in a position to share complete design (CAD) drawings and control software with interested collaborators willing to join us in this documentation of the electromagnetic Mach Effect. It is our hope that these continuing publications that show ever more robust findings documenting what we are observing will soon be reproduced by other universities and collaborators. We anticipate the full characterization of this novel sensor to be completed by the end of 2022. What the project team actually achieves in this semester's independent study will determine if we actually are able to reach those goals.

Expectations and Assessment

While there may remain greater challenges to articulate concrete outcomes for student research fellowships over the summer session (due to institutional definitions and fellowship constraints), it is more in keeping with the normal class/syllabus requirements for independent study research students to create a list of research/course outcomes at the beginning of the new semester that can be used as weekly check-ins, regular milestones and final (course) deliverables and grading. Since the grading system typically serves as a contract between students and faculty, it is important to substitute it with something else in independent study. What is the process of determining the expectations and how is progress to be regularly evaluated when it comes to research courses? While there is no one size fits all solution to the challenge, it is typically best when both the student and faculty are in agreement with not only the level of effort that will be expected throughout the term, but the objective outcomes that would be necessary to achieve to obtain a grade at each level the student is seeking from the course (C, B, A, etc.) It goes without saying that these objective measures need to be jointly agreed upon at the outset of the independent study (allowing always for unforeseen circumstances) but driving to minimize surprises (or disappointments) at the end of the semester if/when outcomes are not achieved. In most instances it takes time for instructors to know what students are capable of in each research challenge and be in a position to not heavily penalize when progress is slow and results are less easily assessed than by "testing" knowledge.

Summary

Students can produce some of their very best work when driven by self-motivation and genuine interest in the topic. Therefore, when resources and opportunity allow, engineering curricula should allow more room for student agency via independent study and summer research interns. While contemporary classroom courses are essential to widen the breadth of the student's knowledge, they should be supplemented, when possible, by such experiences as these which allow for student-led learning experiences. Interestingly, this is when students can often produce their best work. The improvements to the professor's sensor system and the research project results described in this paper speak to the effectiveness of these student-led experiences. Unfortunately, independent study and summer research opportunities remain available to only a fraction of the student body across most college and university engineering programs. More emphasis should be placed on incorporating these types of learning experiences, reflecting the influx of autonomy the students will find in their future careers.

Appendix A

Bucknell University student research fellowship requirements (as opposed to student employees) The wording clearly articulating how research students working on fellowships are engaged primarily in an educational experience as opposed to work-study/ To quote our specific university requirements here: "On the other hand (contrasting to student work-study employees), there are many instances where a student is engaging in scholarly endeavors primarily for the benefit of the student, rather than for the benefit of the University and its faculty/staff, grantor or sponsor. In those situations, the student may be awarded a fellowship or stipend.

Factors that support a determination that a student is not acting as an employee and, instead, is eligible to be a fellowship recipient:

1. The solicitation, notice of award, or sponsorship agreement indicates that the primary purpose of the award is to provide training for selected student participants.
2. The focus is on the education, training and the development of research skills of the student, not on services performed to benefit the university, a professor, a grantor, or a sponsor.
3. The fellowship payments are made to help defray the living expenses during the study period;
4. Deliverables expected of the student are limited to such things as progress reports, academic publications, and presentations, all for the student's educational development.
5. The student is intellectually engaged and contributes meaningfully in determining the focus and direction of the research activities.
6. The student is not required to enter into any patent or other intellectual property agreements, including through agreements entered into by the University on the student's behalf.
7. The student is not required to have performed past services or to agree to perform future services for the University as a condition of receiving the payment (e.g. the student is not required to return as a graduate assistant).
8. Engaging a student tends to slow down, not speed up, the research.

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