A Design-Based Research Course for Biomedical Engineering Students

Ms. Amanda Bacon, University of Illinois at Urbana - Champaign

Amanda Bacon is a Bioengineering PhD student at UIUC primarily working on developing field/point of care biosensors. She received her B.S. in Chemistry from the University of Texas at Dallas. She is interested in science communication and bringing new generations of students and engineers into the field.

Prof. Holly M Golecki, University of Illinois at Urbana - Champaign

Dr. Holly Golecki (she/her) is a Teaching Assistant Professor in Bioengineering at the University of Illinois Urbana-Champaign and an Associate in the John A Paulson School of Engineering and Applied Sciences at Harvard University. She holds an appointment at the Carle-Illinois College of Medicine in the Department of Biomedical and Translational Sciences. She is also a core faculty member at the Institute for Inclusion, Diversity, Equity, and Access in the College of Engineering. Holly studies biomaterials and soft robotics and their applications in the university classroom, in undergraduate research and in engaging K12 students in STEM. Holly received her BS/MS in Materials Science and Engineering from Drexel University and her PhD in Engineering Sciences from Harvard University.

A Design-Based Research Course for Biomedical Engineering Students

Abstract

This paper describes updates to an undergraduate and graduate-level soft robotics design course intended to help students become aware of how research and design work occurs within bioengineering fields, specifically aimed at exposing the hidden curriculum of research to build student confidence. This soft robotics design course, an elective within a bioengineering department, concentrates on academic research and industry applications of robotics in healthcare and health technology. Students were introduced to soft robotics through the engineering principles and material concepts alongside academic research. By using multimodal content such as podcasts, students were engaged beyond the material concepts to consider field impacts as well as open challenges in the discipline. Hands-on workshops developed student confidence in soft robotic techniques and comfort with ideating new solutions. Students researched the state of the academic field as well as spoke to end users about soft robotics use in the healthcare industry, especially regarding medical training and clinical use. Student final projects showed their engagement in academic and industrial applications as well as with the course material. In this paper, we demonstrate multiple efforts that successfully engaged students in the field by decreasing the perceived inability to contribute to this space as academic scientists or within industry. While content is grounded within soft robotics research, expansion to other fields is possible and can help reduce the hidden curriculum by reducing the height of the pedestal academic research is often held up in front of students.

Introduction

Soft robotics is a design-based robotics discipline that leverages multiple engineering disciplines to develop technologies for healthcare and health technologies applications. This field involves the use of low-modulus, polymeric materials to design electromechanical devices. Soft robotics leverages human-centered design, healthcare, and biomedical engineering because of the safety of soft materials, compliance matching with the human body, and bioinspired designs [1]. Soft robots can safely interface with humans. Compared to traditional robots, soft robots replace rigid linkages with programmed polymers and flexible electronics [2]. The popularity of soft robotics as a research field is a recent phenomenon since the early 2010's [3]. In this time soft robotics principles have been applied to the development of bioinspired designs [1], soft grippers of delicate fixtures [4], wearable robots [5], and implantable devices [6]. We previously showed that biomedical and bioengineers are growing contributors to this area, contributing more than they do in traditional robotics research [7]. Providing opportunities for undergraduates to learn about the field at scale in courses can cultivate interest and prepare bioengineering students to contribute to this design-based field to advance health technologies to address pressing medical needs.

We previously reported on development of a soft robotics design elective in a bioengineering department at a large, public university [7]. This course was initially proposed to provide design opportunities to undergraduates early in the curriculum and to MEng students who may be new to engineering, coming from other STEM fields. This paper focuses on updates to the course since its introduction. This paper introduced two course updates and seeks to understand their ability to expose the hidden curriculum of research. First, we supplemented course content with video recorded seminars and podcasts. This was intended to help students understand the career trajectories, challenges, efforts of the researchers behind the journal articles and technical concepts presented in class. Next, we collaborated with staff from a medical simulation center who helped students understand their needs in physiologically and anatomically relevant models. This led to an ideation assignment and an application-focused design project intended to help meet the needs of the simulation partners. Altogether with these course updates, we sought to understand how students engaged with these new elements designed to break down student perceptions of what it takes to be an innovator and researcher in a relatively new field.

Course Learning Objectives:

In this course students will:

- Apply fundamentals of polymer chemistry and sensors to understanding wearable devices and soft robots.
- Read and discuss current literature in the field.
- Build actuators and sensors pictured here using polymer molding and fabrication techniques.
- Design novel advances in bioinspired, wearable, or implantable soft robots.

Understanding Social Networks in Academic Research

The nascency of the soft robotics discipline allows for network analysis among current researchers. To start, we helped students to understand the details of an academic paper that would allow them to start to make these connections. Figure 1 shows an early paper in the field and some of the details that get discussed in class. We help undergraduate students to understand the typical roles of first authors and sometimes we are able to guide them into finding where those authors are now and how their career has evolved. With this we help students discover the network of global researchers in the field. Later in the course, we discuss how soft robotic technologies make it from the lab to commercial products, as there are examples in the field, some even with documented stories of success and failure (Empire Robotics). Altogether, throughout the course we discuss the hidden curriculum of academia.

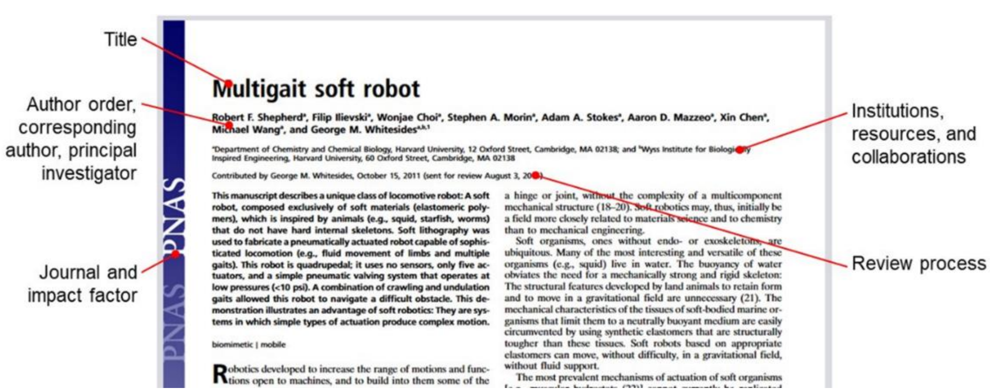

Figure 1. Example of journal article details that are discussed before technical content is covered.

As the class examined publications, the publication industry was explained to students providing background for the academic review process. Confidence in research created by academics is especially important in the era of ‘doing your own research’, and thus educating all students, not just those with academic career plans, on the research publication process is important.

While current literature (journal articles) is the basis for course discussion and course materials, as due to the nascency of the field there are few texts specifically focused on teaching soft robotics design. In this updated offering, we experimented with providing students with relevant journal articles, recorded talks, and a podcast from the same author. During the COVID-19 pandemic, we were able to have students attend free, virtual conferences during the course. While these opportunities have largely ended, we can replicate this in a more sustainable way with recorded seminars freely available on video sharing platforms, and podcasts from the same author.

Results

Students were asked to compare content and intended audience of three media platforms from one academic researcher to engage all varieties of learners and determine the effectiveness of each media mode. We analyzed this data for quality improvement of the course. As this data is not generalizable, it falls under the IRB category of non-human subject research (IRB #21782). Based on prompt answers, Table 1 was compiled using apriori and emergent thematic analysis to determine common answers and feedback about the different media options. Each piece of media did have slightly different content which students picked up on. As the video recorded talk was most similar to the lecture style that students are accustomed to, it was important to see what aspects of alternative media students connected with. Our data indicated that it may be helpful to provide all modes (journal article, video seminar, podcast) for lessons in the future, with a suggested order to help ease students into the topic.

Table 1. Thematic analysis of multimodal course content.

Mode	Feedback theme	Explanation
Video recorded talk	Video supplements technical content (71%)	Being able to see the robot in motion rather than snapshots (helpful visual explanation of concepts); Videos helped to keep pace/interest/attention
Video recorded talk and podcast	Reduced technical jargon (62%)	Use of less jargon also helps keep students (beginners to this field) engaged and focused on broad motivations
Video recorded talk and podcast	More approachable and “human” (43%)	Several students commented on the more human and approachable nature of the podcast and the personal stories told within the research talk which made them prefer that method.
Video recorded talk and podcast	Passive method of gaining information (28%)	Some students prefer having the information “given to them” (listening or watching) than having the “get” the information themselves (as in a paper).
Journal article	Technical detail (58%)	Technical details for replication and characterization of the work were largely found to be extraneous to students who were focused more on results and applications

As shown in Table 1. students identified visual aids as a very important part of their understanding as well as engagement with the information. As this class is largely an introduction to soft robotics, a higher-level discussion of projects especially including the applications was easier for students to digest and this was noted in student's aversion to jargon and dense material. What we found to be especially interesting was the concept of having to work for information through reading rather than being given the information over audio as several students commented on preferring the passive method of learning in the video and podcast.

Delving into the audio delivery of content, we were particularly interested in understanding student perceptions related to podcasts used in engineering classes. We asked students to identify the pros and cons of podcasts as a delivery method for course content. Podcasts are relatively easy to produce and may represent an accessible platform for connecting students with researchers.

Table 2. Student perceptions of podcast content in a soft robotics course.

Theme	**Relevant Quote**
Accessibility and General Audience Appeal	*"The podcast offers explanations that are more digestible for listeners who are not experts in the soft robotics field."*
Engagement Through Informal and Relatable Delivery	*"The podcast was more conversational and also aimed at a general audience, including people with an interest in robotics or surgery."*
Focus on Broader Implications and Real-World Applications	*"The podcast is a very generalized form of delivering information on the current research and provides overview of advances happening in the field of soft robotics."*
Multi-Tasking and Flexibility in Learning	*"A podcast could be advantageous for individuals with a casual interest in the topic or researchers seeking background information while multitasking."*
Introduction to Experts and Their Perspectives	*"For the podcast, the intended audience is those interested in the field of robotics, other researchers, and people who are not familiar with the field."*
Complement to Other Learning Methods	*"The podcast seemed to aim at a broader audience, using a conversational tone that could appeal to those outside the technical sphere. This contrasts sharply with the YouTube seminar and the research paper, which were decidedly more academic and technical in nature."*
Requires Active Listening and Focus	*"When I am watching a video or listening to a podcast, I need to actively make myself focus on what is being said. I also have a hard time digesting things the first time I receive information, and it's a lot easier for me to just reread a sentence or two in a paper rather than having to rewind the video or podcast."*
Broad Audience Range (maybe lower-level understanding)	*"The podcast targeted a broader public audience, providing an overview of challenges and innovations in soft robotics without delving into specifics, making it suitable for listeners with minimal technical background."*

Overall students found the podcasts less formal, more approachable, and easier to understand for those new to the field. Podcasts can act as an opener for curiosity into the field which was demonstrated when students were asked to write interview questions for researchers. Students also commented on the personal stories that the scientist shared in the podcast as giving a better connection to driving purpose. During one lecture, the work of a number of faculty conducting soft robotics research on campus were highlighted. Students were asked to generate questions that could be asked in a podcast interview with those individuals. We used thematic analysis to categorize the types of questions students proposed to understand the content students are most interested to hear. Figure 2 shows the breakdown of the types of questions students proposed for the podcast series. We observed that 27% of questions fell into the category of “more research details”, and 73% of questions were more focused on understanding aspects that aren’t typically get written about in journal articles including the researcher's career, how ideas were conceived, challenges faced and practical applications of the research findings.

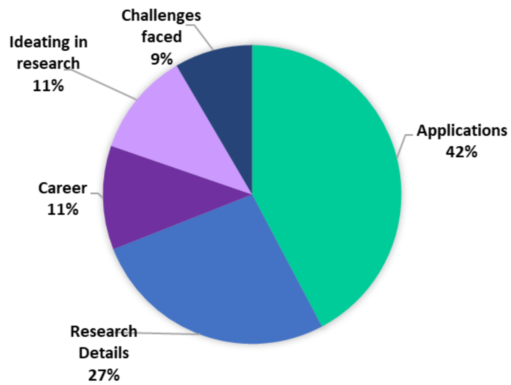

Figure 2. Themes from student responses to “propose a podcast interview question for this researcher”.

Students were largely interested in applications and challenges in the field, an underreported area in most academic fields. Applications and challenges is largely relegated to introduction sections and review papers, while classes may abstract the application to focus on teaching mechanical princes. As students learned the basic techniques, their focus shifted from understanding principles to applying principles in use cases. A case study in bringing research outside the laboratory studied within the class was Empire Robotics. Students followed the path of seeing developed research articles including patent creation to start-up creation including heights of appearance on a late night talk show. While Empire Robotics was unable to become a commercial success, the CTO, John Amend, published a journal article on the lessons the team learned in attempting to create a soft robotics business [8]. Amend et al. delve into how academic characterizations of systems differs from commercialization system needs and students discussed the differences needed to demonstrate a new concept versus use in industry. Students also learned about the work done by Disney in soft robotics for interactive entertainment robots [9]. While this course is primarily healthcare application focused, through case studies of individual soft robotic startups and developments within large companies, students were exposed to a variety of applications such as art and entertainment, virtual reality, labor exosuits, and food handling.

Applications of Technical Concepts: Clinical Observations and Design Project

Through the first half of the class, students learned the principles used throughout soft robotics through journal articles and focused further upon application as their grasp of the common techniques improved. Principle knowledge was learned not through just lecture and discussion but hands on use through a set of four build workshops and the second half of the class focused on a design project focused on application and introducing clinical usages of soft robotics which are further discussed below.

To supplement fundamental learning through lectures and papers, four hands on building workshops were developed. In brief, the four builds covered; pneumatic actuators [10], tendon actuators [11], pneumatic muscle actuator [12], and vacuum gripper [8] provide an overview of general techniques used to develop multitudes of soft robots. Each of the four build reports included a literature review of the applications of the technique, as well as documentation of the build and analysis of the build and further applications or development. Seen in Figure 3. students were beginning to connect the techniques to further applications through each build's section on further applications.

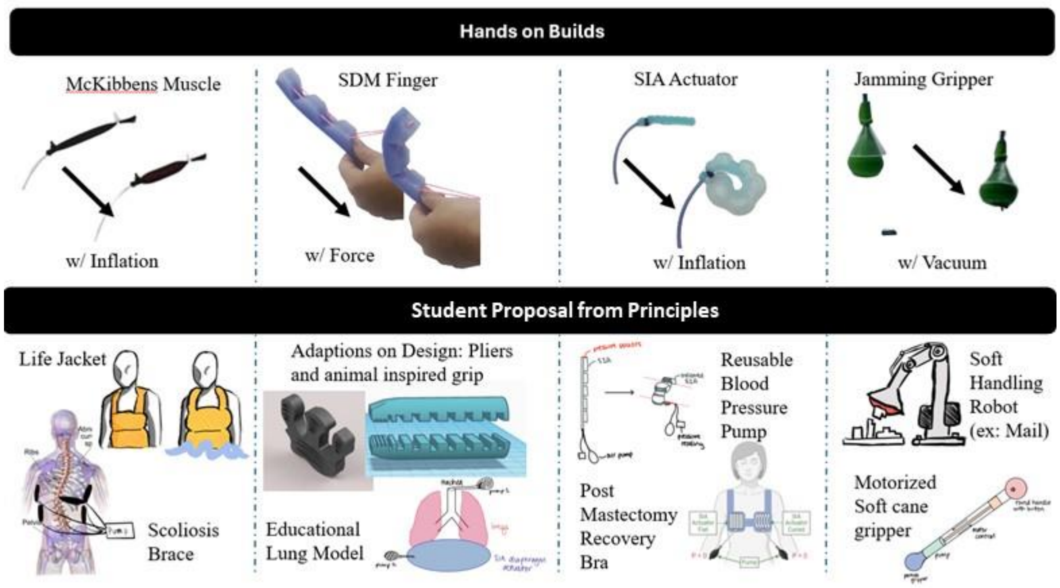

Figure 3. Top: Each hands-on build workshop: McKibbens Muscle, Tendon Driven Finger, Silicone Pneumatic Actuator, and Jamming Gripper. Below: Student diagram and proposals showing application of each foundational build.

This was further built upon by a meeting with end users of some soft robotic designs within the Jump Simulation Center for medical training. There, students were able to use several task trainers used to train medical students and residents on skills before rotations. Students had the opportunity to interact to understand how soft robotics was currently being used in physician training. They were also told about the areas that these trainers and manikins had deficits compared to reality. Students developed new ideas seen in Table 3 to improve upon existing technology including creating new suggestions such as bed sore skin and muscle models so trainees could learn to identify ulcers through touch and look before seeing patients. A common theme was the lack of automation within these manikins or trainers requiring simulation technicians to work the stage or otherwise creating an unrealistic experience.

Table 3. Simulation Center Trainers, Deficits and Solutions posed by Students

Trainer	Problems	Solutions
Birthing Manikin: 	• Can only do natural birth simulation • No realistic body fluid as part (Sim Techs) • Does not always work as expected	Develop an actuator that allows for stuck/smooth births simulation by choice Develop an actuator for contraction simulation Add built-in mechanisms for realistic lubrication Develop self healing C section manikin Construct manikin with realistic muscle/skin feel
IV Arm: 	• Need to buy two arms for vein/artery IV • No automation in artery version (hand pumped by trainer)	Develop actuator to create simulated pulse Develop underskin pneumatic to simulate IV for different levels of body fat Use soft robotics to model scar and skin models so training can occur on 'non ideal' patients
Intubation: 	• Model struggles with incorrect flexibility/material of body parts (teeth and tongue) • No working organ so cannot see impact • Incredibly costly if any part breaks (must rebuy completely new model)	- Use soft robotics to model correct strength and feel of model such as teeth and tongue for realistic - Develop pneumatic lungs to see impact of correct intubation - Reduce probe force damage through silicon actuators on probe tip - Create detachable model so replacement costs are part specific rather than entire model replacement
Laparoscopy: 	• Largely used to practice vision and tool use • No simulated body parts/organ	Develop organ representation with simulated surgery options Use viscous material to simulate inner organs and body fluid

With experience in literature review, current products, and analysis from their own builds, students embarked on a 7 week soft robotic design project to propose a soft robotics solution. No area or set of problems was proposed in order to encourage broad creativity from students. The final project inspirations were taken from a variety of places shown in Figure 4. The final projects were able to be grouped based off inspiration from founding principles taught in class and in hands on workshops based off assignments where students developed new ideas using the techniques learned. Students also developed projects using principles not demonstrated in the hands on workshops showing further engagement, largely showcased in industrial applications. As the class was healthcare focused along with the talks with end users of soft robotic medical technology, an unsurprising large amount of final projects were developed for that area. Beyond healthcare applications, students were given a limited basis for industrial applications through the case study on Empire Robotics and industrial discussion as well as hands on workshops focused on principles largely used in medical technology. Despite that, some students developed final projects using principles of soft robotics not studied in depth in class, demonstrated in the industrial application final projects in Figure 4.

Figure 4. Each circle represents where the inspiration for a final project was presented from (as described by students). Light blue represents prototypes that are focused more on principle and technique, inspired by the 4 hands-on build workshops. Light green represents prototypes that are focused on solutions for healthcare, inspired by the Jump Simulation Center. Light yellow represents prototypes that are focused on solutions for entertainment and manufacturing, inspired by lectures.

As the final assignment was an IEEE style conference paper, students got experience in the practices of academic research, demystifying the concept of research to be more approachable for them rather than only being done by a separate group of people. Beyond the engagement in all activities throughout class shown in the final proposals, several students opted to submit their work to University of Minnesota Medical Device Design Showcase with at least one acceptance. Through this course, students not only learned soft robotics fundamentals, but got experience in the actual mechanisms of academic research to a level that they were able to participate in undergraduate research.

Evaluating Engagement: Student Feedback on New Course Elements

While engagement through incorporation of the proposal ideas conveyed to them through a variety of activities and mastery of basic soft robotic techniques through their prototype design and development, we also sought student personal opinions with informal early evaluation alongside formal course evaluation. Opened ended questions and thematic analysis is shown in Table 4, while ranking questions are shown in Figure 5.

Table 4. Informal Early Feedback from Students

Questions	Themes within the Data	Quotes	Response from instructional team
What activities helped you best learn the material?	Students preferred the (1) hands-on build as well as (2) lectures/talks with several students mentioning the (3) Soft Robotics Toolkit as a valuable resource. (77%, 44%, 22%)	"*The lectures and hands on builds have best helped me learn the material. The lectures provide really good examples that are easy to comprehend, and the hands on builds allow me to build a soft robot for myself. This helps me really visualize the actuation process.*"	Although the class size is growing, we will find ways to keep the hands-on element in the course.
What resource do you need to be successful in prototyping for the final project?	Students wanted more (1) information on what materials were best for their uses as they started their prototyping efforts as well as (2) CAD guidance for developing molds. (33%, 33%)_	"*A little bit more on the material side of robotics." "I think we just need guidance on CAD and which materials are feasible for our project.*"	We hosted CAD workshops and had CAD experts in the lab during project build days.
What is best part of the course?	Students were largely unanimous in enjoying the hands-on builds within the lab time. (100%)	"*I really enjoy the projects and actually being able to create what we are learning about" / "I like the builds that we do they really help me understand what we are learning in class.*"	We hosted set lab build days so students could work their own build proposals during class time, providing in class build time.
What is least useful part of the course?	Generally students found the homework problem sets the least helpful in cementing learning as well as several students commented that the journal club presentations (completed by graduate students in the course) felt disjointed. (32%, 28%)	"*The problem assigned during class, can be kind of tricky, and more outside classtime than expected."/ "Problems, but they are alright" / "I enjoyed the journal clubs however sometimes its hard for me to stay focused when the topic is very advanced making it hard to follow along.*"	In the future, we may move journal club to video recordings so that it takes up less class time.
What would you change to make	Many students thought the problem sets should be removed, while	"*I would have more hands on build sessions, but I believe this course is extremely well*	We believe that weekly problems are critical for students to

the course better?	others wanted more builds/time for builds. (22%,19%)	*structured as is."/ "I would remove the weekly worksheets and instead maybe just brainstorm a new design*"	demonstrate understanding and reinforce the mathematical element required in design.

Results from the open ended questions on the informal early feedback survey, showed that students preferred the active learning style of the hands on workshops. Students did not prefer the traditional homework assignments that tested understanding of soft polymer mechanics through equations and analysis of presented data. As the builds were an engaging way to demonstrate principles of soft robotics, build days were set aside in the later half of the class for students to continue prototyping their final projects with instruction feedback. Through the survey, students wanted more time for builds as well as more support with their final projects such as 3D modeling assistance as they created molds for soft polymer robots.

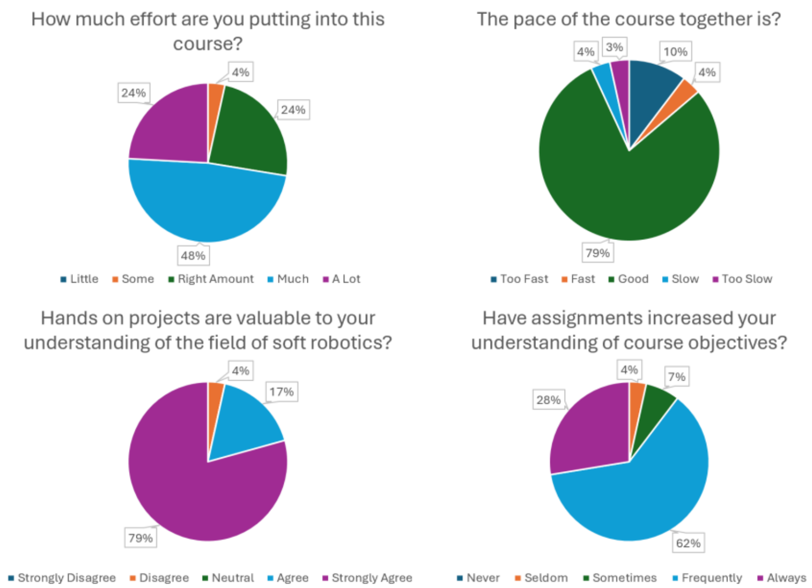

Figure 5. Likert scale questions included within the informal early feedback course assessment to assess how class changes resonated with students

With Likert scale and open-ended questions together, the class largely found the activities done to enhance engagement useful. Through analyzing the informal feedback survey shown in Figure 5, one student found the hands-on portion of the class not useful, but 100% (40/40) of students who filled out the best part of the class question mentioned the builds validating the importance of the previous work as well as it came up frequently (77% of answers) as one of the best ways students felt they learned.

As the class largely goes through academic journal articles and quick builds developed to develop hands on learning of the soft robotics fundamentals and then transitions into the students proposing a solution that they will be prototyping as their final project, information such as the pace of the class aligning with students learning pace was excellent. Beyond commenting on the course pace and assignments, many students opted to notate how connected they felt shown in Table 5. While many focused on the confidence and progress, they have made in soft robotics, general appreciation for engineering came through in seeing design process to prototype as well as demonstrated success in problem solving.

Table 5. Student Engagement Comments

Theme	Relevant Quote
Captivation with Topic	*“I love that I was able to come in with little to no background on the topic and I now enjoy the topic and am very interested in following the latest technology and seeing the impact it may have in the future.”*
Design/Prototype Engagement	*“I really like the material, but I think the best part has been being forced to ideate/come up with novel applications or designs in our problems.” / “The best part is the design project. Its really fun to come up with something and see it all the way through.”*
Accomplishment Engagement	*"I really enjoyed spending time in [lab] working on the hands on build as they actually made me really excited about all the possibilities soft robotics has. Also the class makes me feel accomplished and proud of myself when I can successfully complete these builds so it helps with my self doubt as an engineer.”*
Broad Process Engineering	*The lectures and hands on builds have best helped me learn the material. The lectures provide really good examples that are easy to comprehend, and the hands on builds allow me to build a soft robot for myself. This helps me really visualize the actuation process.*

Discussion

The structure of this class was designed to engage students of all levels (open to undergraduate and graduate students) in the nascent field of soft robotics. The hands-on workshop topics were selected for general ease and speed of fundamental learning to convey the principles to students. This bolstered student engagement with the field as it built basic principle understanding alongside confidence in problem solving with field specific techniques. The use of multimedia was used to introduce students to varying levels of science communication, and students appreciated the high-level discussion of problems and challenges as well as felt more engaged with the content aimed at more broad audiences such as the seminar and podcasts. By focusing on education about the fields challenges and research problems alongside the technical principle education, students felt connected to the potential applications that they could potentially build. Providing students with a project starting from ideation through multiple prototype iterations to presenting their work in a conference style paper, students were able to participate in a sliver of the process of academic research and industrial product development. These activities are not field specific and can be taken to explicitly break down the barriers students often self-impose between themselves and researchers. This study is limited as the course is largely an elective (54% of students take as an elective) thus self-selecting for students interested in the topic which can affect engagement levels. This course is open for undergraduates and gradate students which lends to a more broad approach at content due to the differences of preliminary education each student has. A course aimed towards advanced students of soft robotics may be able to more concretely test the effective engagement of hands on learning as the need for teaching field fundamentals could be skipped. Further studies on the effectiveness of multimodal content including testing for differences in comprehension and recall of information based on platform should be completed.

Through this class, students engaged in a field popularized in the 2010s and were able to learn the basic principles and techniques as well as engage in codified method of research process by identifying a problem along with current research work and then designing and prototyping a proposed solution. This allows students to break through the perceived mysterious process of research and become active participants alongside creating trust in the academic system.

Acknowledgements

This work was funded in part by the Strategic Instructional Innovations Program in the Academy for Excellence in Engineering Education in the Grainger College of Engineering at the University of Illinois Urbana Champaign.

References

[1] S. Kim, C. Laschi, and B. Trimmer, “Soft robotics: a bioinspired evolution in robotics,” *Trends in Biotechnology*, vol. 31, no. 5, pp. 287–294, May 2013, doi: 10.1016/j.tibtech.2013.03.002.

[2] H. Lim, H. S. Kim, R. Qazi, Y. Kwon, J. Jeong, and W. Yeo, “Advanced Soft Materials, Sensor Integrations, and Applications of Wearable Flexible Hybrid Electronics in Healthcare, Energy, and Environment,” *Adv. Mater.*, vol. 32, no. 15, p. 1901924, Apr. 2020, doi: 10.1002/adma.201901924.

[3] M. Cianchetti, C. Laschi, A. Menciassi, and P. Dario, “Biomedical applications of soft robotics,” *Nat Rev Mater*, vol. 3, no. 6, pp. 143–153, Jun. 2018, doi: 10.1038/s41578-018-0022-y.

[4] C. Majidi, “Soft Robotics: A Perspective—Current Trends and Prospects for the Future,” *Soft Robotics*, vol. 1, no. 1, pp. 5–11, Mar. 2014, doi: 10.1089/soro.2013.0001.

[5] P. Arens *et al.*, “Real-time gait metric estimation for everyday gait training with wearable devices in people poststroke,” *Wearable Technol.*, vol. 2, p. e2, 2021, doi: 10.1017/wtc.2020.11.

[6] C. J. Payne *et al.*, “An Implantable Extracardiac Soft Robotic Device for the Failing Heart: Mechanical Coupling and Synchronization,” *Soft Robotics*, vol. 4, no. 3, pp. 241–250, Sep. 2017, doi: 10.1089/soro.2016.0076.[1] M. Hammond, V. Cichella, and C. Lamuta, “Bioinspired Soft Robotics: State of the Art, Challenges, and Future Directions,” *Curr Robot Rep*, vol. 4, no. 3, pp. 65–80, Sep. 2023, doi: 10.1007/s43154-023-00102-2.

[2] N. Elango and A. A. M. Faudzi, “A review article: investigations on soft materials for soft robot manipulations,” *The International Journal of Advanced Manufacturing Technology*, vol. 80, no. 5–8, pp. 1027–1037, Sep. 2015, doi: 10.1007/s00170-015-7085-3.

[3] L. Cecilia, *Soft robotics: trends, applications and challenges*.

[4] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, “Soft Robotics for Chemists,” *Angewandte Chemie International Edition*, vol. 50, no. 8, pp. 1890–1895, Feb. 2011, doi: 10.1002/anie.201006464.

[5] C. Walsh, “Human-in-the-loop development of soft wearable robots,” *Nat Rev Mater*, vol. 3, no. 6, pp. 78–80, May 2018, doi: 10.1038/s41578-018-0011-1.

[6] E. T. Roche *et al.*, "Soft robotic sleeve supports heart function," *Science Translational Medicine*, vol. 9, no. 373, p. eaaf3925, Jan. 2017, doi: 10.1126/scitranslmed.aaf3925.

[7] H. M. Golecki, J. Robinson, C. Cvetkovic, and C. Walsh, "Empowering Students in Medical Device Design: An Interdisciplinary Soft Robotics Course," *Biomed Eng Education*, Apr. 2024, doi: 10.1007/s43683-024-00143-9.

[8] J. Amend, N. Cheng, S. Fakhouri, and B. Culley, "Soft Robotics Commercialization: Jamming Grippers from Research to Product," *Soft Robotics*, vol. 3, no. 4, pp. 213–222, Dec. 2016, doi: 10.1089/soro.2016.0021.

[9] J. Kim, A. Alspach, I. Leite, and K. Yamane, "Study of children's hugging for interactive robot design," in *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, New York, NY, USA: IEEE, Aug. 2016, pp. 557–561. doi: 10.1109/ROMAN.2016.7745173.

[10] A. H. Greer *et al.*, "Soluble Polymer Pneumatic Networks and a Single-Pour System for Improved Accessibility and Durability of Soft Robotic Actuators," *Soft Robotics*, p. soro.2019.0133, Jun. 2020, doi: 10.1089/soro.2019.0133.

[11] S. Berndt, M. Herman, D. Holland, and C. J. Walsh, "The SDM Finger: Teaching Engineering Design Through a Soft Robotics Workshop," *Science Scope*, vol. 43, no. 4, pp. 14–21, 2019.

[12] "Modeling and control of McKibben artificial muscle robot actuators," *IEEE Control Systems*, vol. 20, no. 2, pp. 15–38, Apr. 2000, doi: 10.1109/37.833638.