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Novel Mechatronics as a Multidisciplinary Introduction to Engineering Fundamentals

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Introduction

In this complete research study, we analyzed the efficacy of portraying introductory engineering principles through classroom activities in mechatronics. The current state of technology is one in which most systems require the interdisciplinary contributions of multiple engineering fields. It is highly important that students of engineering acquire the proper exposure to this interdisciplinary nature in the curriculum, adapting with the evolution of economic incentives. Substantial economic and industrial investments in the field of mechatronics stands as a particularly notable example of this ever-rising collaboration in industry. We adapted the principles of mechatronics as a multidisciplinary field into the first-year engineering curriculum through a hands-on activity. Mechatronics-based activities have been studied for a range of applications such as in developing entrepreneurial mindsets [1] or to analyze and reduce gender disparities in engineering fields [2].

However, we aimed to uniquely create and implement such an activity in a manner emphasizing these fundamentally collaborative outcomes to equip future generations of engineers. We developed a novel mechatronic arm construction activity complete with a supporting instructional manual and questionnaire targeting specific features of the mechatronic system. The activity was employed in two main phases: an initial "pilot" phase and the finalized phase. Out of the eight total classes the activity was administered to, only the first two were a part of the pilot phase of which was meant to gauge the exact number of mechatronic arms required for each section and/or to modify any given handouts.

Students provided an assessment of the personal benefits of the activity through a post-activity survey. This paper conclusively demonstrates that mechatronics is an exemplary field for showcasing the interdisciplinary nature of mechanical engineering. The findings affirm that integrating diverse disciplines within mechatronics not only enhances student learning but also fosters the collaborative skills essential for future engineers.

Background and Necessity of Invention

Creating an activity that encapsulated the objectives of this study required intent on which engineering fields to address. We determined, with the immense presence of mechatronics and robotics in industry, an activity oriented on the construction of a robotic arm targeted the more prevalent fields in the current job market: mechanical, electrical, and computer engineering. However, major restrictions arose during the search for commercially available robotic arms: these coming from the interplay of cost, complexity, and availability of components. Under reasonable cost, the arm itself would hardly be a challenge for students to construct; for beneficial complexity, the cost of the machine would be beyond the scope of available funds. In nearly all cases, only the mechanical frame of the robot could be constructed as well, with electronics largely being self-contained or “plug and play.” Therefore, the necessity arose for the creation of a system that fulfilled the proper requirements.

We developed a novel 3D printable mechatronic arm with features allowing for emphasis of multidisciplinary engineering principles. The 5-axis arm consisted of a custom-made 3D printed mechanical frame, commercially available motors and microcontrollers, electronics that could be safely constructed on an open breadboard, and pre-uploaded code that facilitated quick verification on successful construction of the arm. In this manner, we created a machine that, when constructed, fully displayed the interdisciplinary meshing of many engineering disciplines while requiring the builders to work collaboratively and apply problem-solving techniques not beyond the reasonable limit of the first-year curriculum.

Activity Setting and Course Expectations

This study was employed in the Engineering Fundamentals course at Saint Louis University. The course is designed to provide, among other learning objectives, exposure to the six engineering majors offered at our institution: Aerospace, Biomedical, Civil, Computer, Electrical, and Mechanical Engineering. The course is organized into eight sections, each with a maximum of 24 students, with sessions lasting no longer than 110 minutes. Six instructors —one from each major—rotate among the eight sections over six weeks to present their specific discipline, facilitating interactive activities introducing the fundamental concepts and approaches of each field to students. The course creates a dynamic and comprehensive exploration of the various engineering programs, fostering student engagement as they discover each major.

The mechatronic arm construction activity was utilized in the Mechanical Engineering Day: mechatronics is a prominent field adjacent to mechanical engineering, in which the mechatronic arm stands as one of the most iconic and utilized systems in contemporary industry and research. Figure 1 displays a group of students in the middle of building their mechatronic arm kit. The activity functions particularly well for Engineering Fundamentals as it fulfills the student learning objectives in a holistic manner. These specific course objectives are outlined in Table 1 below. The modularity of the activity notably allows for adaptation to nearly any relevant course environment through alteration of the associated handouts and/or supplementary material for the construction process. Over 170 students participated in the activity in total.

Figure 1. Four students focused on constructing the electronics.

Table 1. Course outcomes of Engineering Fundamentals.

Objective 1	Understand the engineering problem-solving process.
Objective 2	Utilize estimation techniques to conduct quick calculations on order of magnitude, energy, force, and mass balance assessments.
Objective 3	Apply algorithmic thinking tools - flowcharts and pseudo codes - to solve engineering problems.
Objective 4	Identify the key roles, activities, necessary skills and professional/social responsibilities for a career in at least one engineering major offered at School of Science and Engineering.
Objective 5	Recognize that both personal and social context shapes all learning.
Objective 6	Characterize how the experience of learning through a distinct disciplinary or interdisciplinary mode of inquiry shapes knowledge of ourselves, or communities, and our world.
Objective 7	Reflect on learning experiences to arrive at a deeper understanding of who they are as scholars and citizens.
Objective 8	Evaluate the ways in which new knowledge illuminates routes towards future action, and identify possible actions one might take in the service of humanity.
Objective 9	Identify, evaluate, and utilize a variety of SLU library source materials to complete a course assignment.

Methods

The Mechatronic Arm

The mechatronic arm is comprised of a 3D printed mechanical frame of PLA secured with M4, M3, and M2.5 screws. All components were custom modeled in SolidWorks. Movement is performed by four integrated MG996R 55g servo motors and a NEMA17 stepper motor controlling five degrees of freedom. Electrical wiring is contained on a 30-row conventional breadboard with wires positioned in such a way that allows for microcontrollers and/or printed circuit boards to be implanted or removed with ease. A PCA9685 motor driver, A4988 stepper driver, 12-to-6-volt buck converter, and Arduino Nano board were used for bulk servo motor control, stepper motor control, cost-effective voltage modulation, and program execution respectively. The principal microcontroller (Arduino Nano) maintained a USB-C communication port for easily accessible user programming.

The low cost of materials and commercial accessibility of replacement parts removes a barrier of cost in conventional constructable mechatronic arm systems. The entire system is assembled simply with a crosshead screwdriver and, optionally, needle-nosed pliers. The construction of the mechanical frame exists as an effective way to portray principles of mechanics and mechanical interactions, while the construction of electronic components offers insight into electrical circuit creation and controls while accentuating the necessity of collaboration between mechanical and electrical engineering in an interactive manner. In a similar fashion, allowing users to easily observe and customize the programming of the mechatronic arm assimilates the third targeted engineering field, computer engineering, into the educational repertoire of the construction process. Minor faults were intentionally incorporated into the mechanical frame to stimulate the constructor's problem-solving skills via conceptual improvements, of which were emphasized by a post-construction questionnaire to be elaborated on in further sections.

The system excels in an instructor-student class environment, as it allows the instructor to alter the complexity of the construction as necessary and actively address the engineering principles being conveyed by the invention at an arbitrary depth. The markedly low production costs due to material choice, open access to mechanical and electrical components, ease of programmability, intentional flaws to more effectively educate on multidisciplinary engineering principles, variable complexity, and the intuitive assembly/disassembly all serve to benefit the builder's educational experience without requiring significant effort from the facilitator. A total of six of these mechatronic arms were built for the purpose of the activity, with an average cost of only $90 per arm. The design of the arm underwent three main stages, of which can be seen in Figure 2:

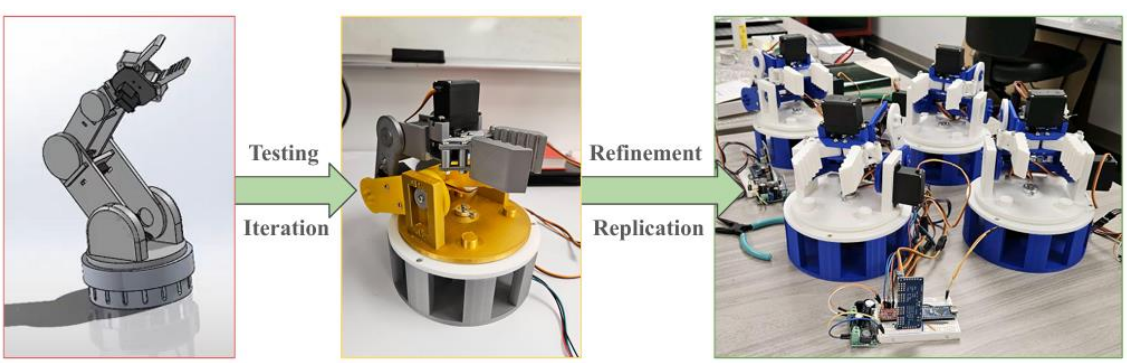

Figure 2. The three stages of development of the mechatronic arm. Left: stage 1 (ideation). Middle: stage 2 (iteration). Right: stage 3 (finalization and replication).

Activity Overview

An introductory presentation was given at the beginning of the activity touching on the invention process and on mechatronics as an industry. The presentation also served to orient students towards the end goals of the activity, with the flowchart below (Figure 3) being provided and discussed in detail prior to giving the appropriate materials out:

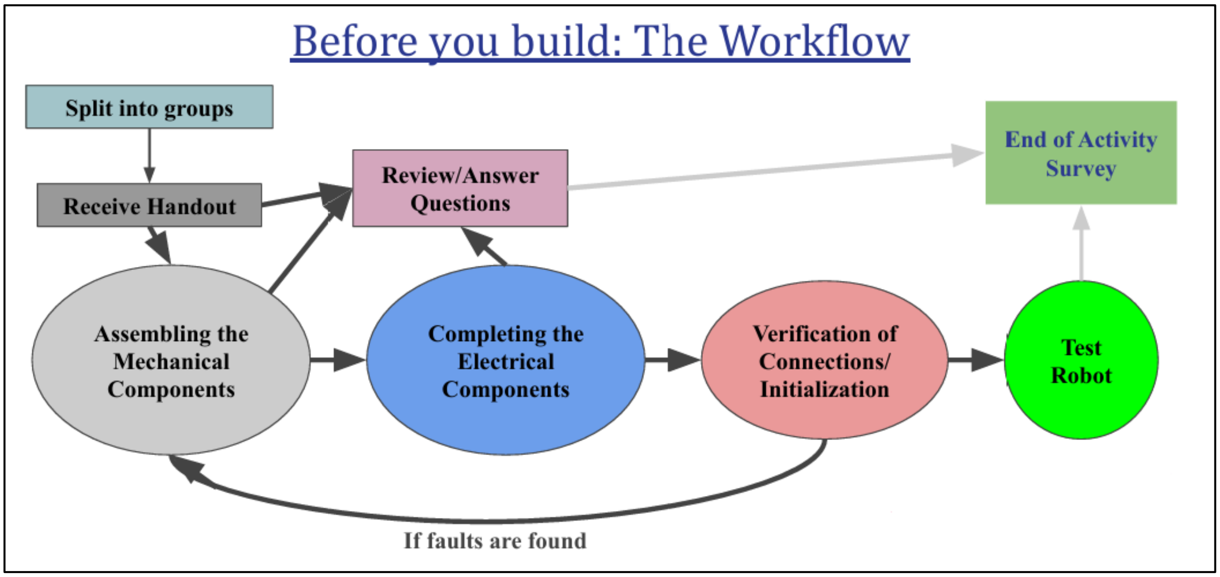

Figure 3. Activity flow chart provided to students.

To detail the expectations: students would begin by separating into the same number of groups as robot kits available (nominally, six kits were used, so students would split into groups of six). With a maximum of 24 students to a class, groups contained no more than four students. Upon group formation, kits of the unconstructed mechatronic arm components with the appropriate handouts —to be detailed in *Activity Handouts and Complementary Documents*— were provided (for the pilot phase, four arms were available, while the finalized activity was administered with six total arms).

Following the instructions, participants began by building the mechanical frame. This included incorporating the motors and 3D printed components correctly given the proper screws and screwdriver. After completing the mechanical construction, students were instructed to ask for the electronic components. This brief verification step was crucial in maintaining proper time management and risk mitigation. Construction of electronics included correctly placing various printed circuit boards on a pre-wired breadboard and connecting external motor wires such that the full control circuit was completed. Following this step, the group would then ask for a second verification where an instructor or teaching assistant would confirm the proper wiring and motor-controller integration.

Upon confirmation, the instructor or teaching assistant would connect a single 12-volt battery to the proper breadboard terminal and, using a cable suited for USB-C based communication, upload a pre-made program through the Arduino IDE to the principal microcontroller. The program executed a simple “grab and drop” movement that showcased the complete functionality of each rotational axis. Assuming no student-controlled faults were observed, this functionality test concluded the activity. Congruent to the building process, students were implored to review and answer the problems on the questionnaire handout as the construction progressed at each stage. Finally, each participant would be guided to complete the post-activity survey assessing specific outcomes of the project.

Activity Handouts and Complementary Documents

Instructional Manual

The instructional manual was structured in six parts: the first four detailed the construction of the mechanical components in a sequential joint-by-joint fashion, with the final two parts delineating the assembly of the electronic modules on a pre-wired breadboard. Specifically, part one covers the assembly of the arm base of which contains the stepper motor and principal rotation axis structure (the “S” joint). Part two requires students to develop the principal forward-backward control piece (the “L” joint). Part three introduces the secondary forward-backward control via a coupling to the L-joint (the “U” joint). Part four details incorporation of the axes controlling the claw movement and gripping mechanism (the “wrist” and “claw grip” joints respectively). Upon completing these sections, students then followed part five of which guided wire organization, emphasizing the importance of uniformity in electronic connection preparation. Finally, part six followed the assembly of the electronic circuit.

To ensure the activity was performed in a timely manner, breadboards were pre-wired, with the students needing to place the microcontrollers and printed circuit boards in their appropriate locations. Students were provided Figure 4 alongside descriptions of exact board placements to complete this section. Figure 5 shows the step-by-step progression of the mechatronic arm’s construction according to the six build phases.

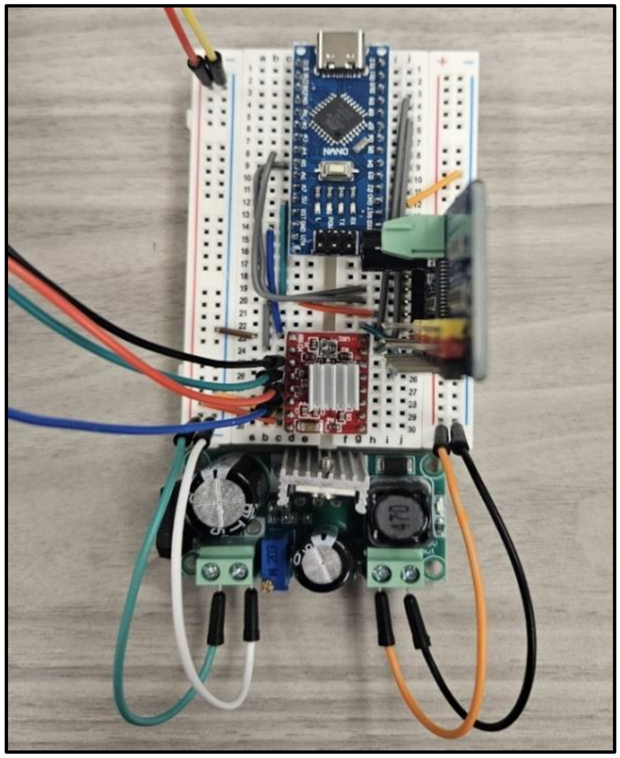

Figure 4. Image of the completed circuit provided to students in the instructional manual.

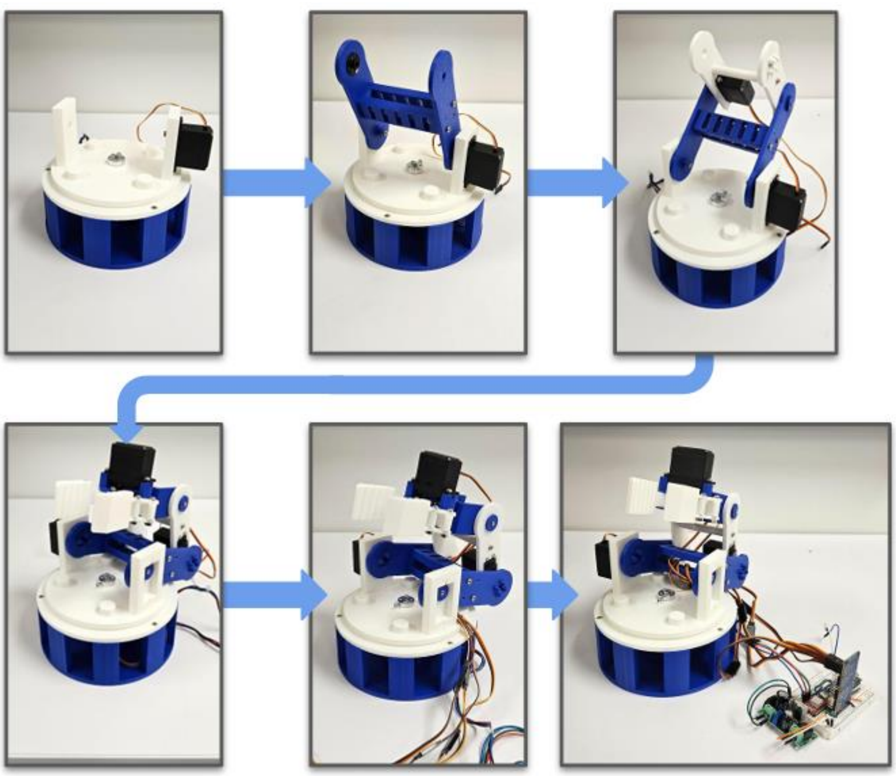

Figure 5. Sequential phases of arm construction from part 1 (top-left) to part 6 (bottom-right).

Questionnaire

The express purpose of the questionnaire was to guide students towards unnecessary or sub-optimal features of the mechatronic arm and to consider what a more refined model would look like. These features include protrusions in the S-joint that serve no purpose and require extra material to 3D print the segment, a bridge connecting two pieces that has two secured points instead of the ideal three, and the nature of reduced fidelity in 3D printing compared to precision machine manufacturing of parts. Furthermore, certain questions pointed out principles of mechanics such as constrained motion and dynamics.

Like the activity as a whole, the questionnaire holds high utility in its versatility: indeed, if the activity were to be brought to a course in engineering dynamics, one can imagine questions related to precise relative motion calculations given motor torque specifications. The exact questions asked to the students in Engineering Fundamentals are documented in Table 2.

Table 2. Problems proposed to students in the questionnaire handout.

Question 1	Did your robot complete the task? (YES/NO)
Question 2	On close inspection, you can see that many screw holes were not printed with threads but were instead given threads post-print. Why is it difficult for a 3D printer to make such precise features like threaded screw holes?
Question 3	When securing the 4-hole bind, you are instructed to place the screws in diagonal patterns. Why is this more effective than placing all screws directly adjacent to each other?
Question 4	The 1-hole bind is noticeably less secure than the 4-hole bind. Why is this? What do you think the optimal number of secured points for any bind is (i.e. what do you think the smallest number of screws needed for a fully secure bind is)? *Hint: how many points are needed to define any plane?*
Question 5	Upon analyzing the claw, there are two hinges that control the movement of each grip. Why two? What would happen if we simply attached each grip to a single hinge?
Question 6	When designing/engineering anything, every component should have a "why": a tangible reason for its existence in the greater structure/function. Are there any parts of the robotic arm that do not seem to have this "why"? In other words, is there any particular part of a component that doesn't seem to have a reason for existing? If so, which part? *Hint: did you use every feature of the Shoulder Joint's structure?*
Question 7	*(1 response per group member)* No design is perfect; many parts of the robot can be improved using a new perspective. Whether it be mechanical, electrical, or movement/code-based, how would you improve the robotic arm project as a whole? *Vetted responses will end up in future versions of the robotic arms.*

Post-Activity Survey

After completing the construction and verifying the functionality of the mechatronic arm, students were instructed to complete a short, 14 question survey (12 multiple choice, 2 short answer). The questions were separated into six categories to probe the different outcomes of the activity: general insight, understanding (clarity), satisfaction, understanding (outcomes), collaboration, and general comments/suggestions. The exact "questions" were in fact statements that students would rate their level of agreement with through a five-point scale: strongly agree, somewhat agree, neither agree/disagree, somewhat disagree, or strongly disagree. In this manner, we understand the students' experience through a holistic lens, also inviting constructive criticism for subsequent activity iterations. Table 3 holds the breakdown of all 14 statements in their respective categories as seen by the students:

Table 3. Survey statements students were to respond to after the activity.

General Insight	
Statement 1	This activity encouraged me to think deeply.
Statement 2	I gained valuable insights into design processes because of this activity.
Statement 3	I want to look in to doing my own personal design project due to my experience with this activity.
Understanding (Clarity)	
Statement 4	The instructions were easy to follow and execute.
Statement 5	I had all the resources necessary to comfortably complete the activity (instructions, supplementary materials, references, etc.).
Satisfaction	
Statement 6	I was satisfied with the activity's complexity.
Statement 7	The activity was engaging and enjoyable overall.
Understanding (Outcomes)	
Statement 8	I feel more equipped to interpret/analyze mechanical systems because of the activity.
Statement 9	I have a greater understanding of how mechanical and electronic systems mesh together because of this activity.
Statement 10	The way different fields in engineering (Electrical, Mechanical, Computer, etc.) contribute to each other feels more intuitive after this activity.
Collaboration	
Statement 11	I was able to play an active role in my group's success in the activity.
Statement 12	I felt like I was able to contribute to my team for the majority of the activity.
Comments and Suggestions (Short Answer)	
Statement 13	My favorite part of the activity was:
Statement 14	If I could change anything about the activity, it would be:

Results and Discussion

Survey responses in each phase were overwhelmingly positive. In the pilot phase, the most consistent suggestion was to reduce group sizes and increase instructional clarity. A common suggestion in the finalized phase was also to create a more easily followable manual. 44 students participated in the pilot phase, with 127 students participating in the finalized activity.

Of these groups, each survey response was given a certain amount of quality points. I.e. Strongly Agree, Somewhat Agree, Neither Agree/Disagree, Somewhat Disagree, and Strongly Disagree were given values of 4, 3, 2, 1, and 0, respectively, and summed across all responses. Total quality points were normalized based on the number of responders; for example, the pilot phase normalized sum is equal to the total quality points divided by 44. These calculations are in Table 4, with the relative response distributions across each agreement level contained in Figure 5. Furthermore, a graphical representation of all compiled responses for each level of agreement is presented in Figure 6.

Table 4. Quality point totals from survey responses in different phases and in total.

Question #	Pilot Phase	Finalized Phase	Total Responses
1	145	386	531
2	154	408	562
3	134	354	488
4	119	356	475
5	159	435	594
6	154	427	581
7	160	444	604
8	126	389	515
9	128	408	536
10	146	425	571
11	160	463	623
12	143	449	592
Normalized Totals	**39.27**	**38.93**	**39.02**

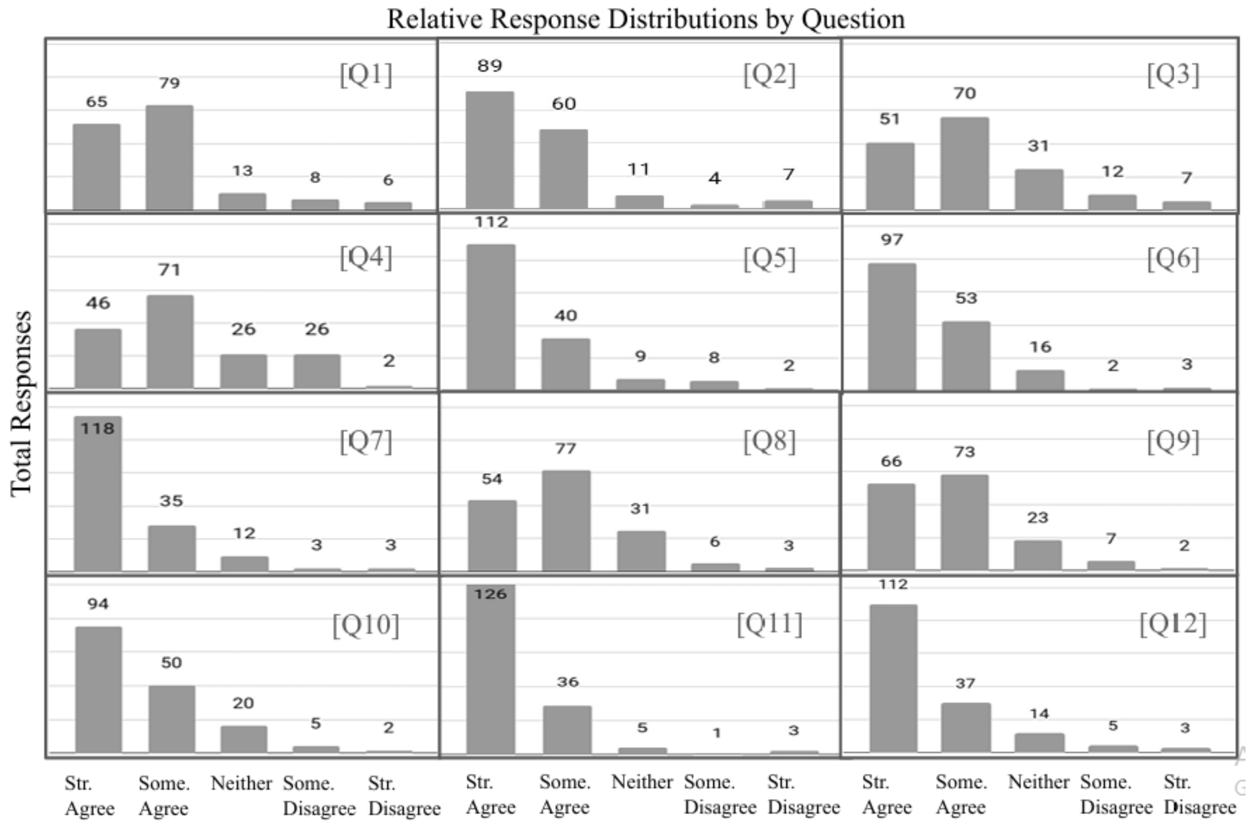

Figure 5. Distribution of responses by question number (in brackets). Graphs are normalized to show a maximum of 125 total responses.

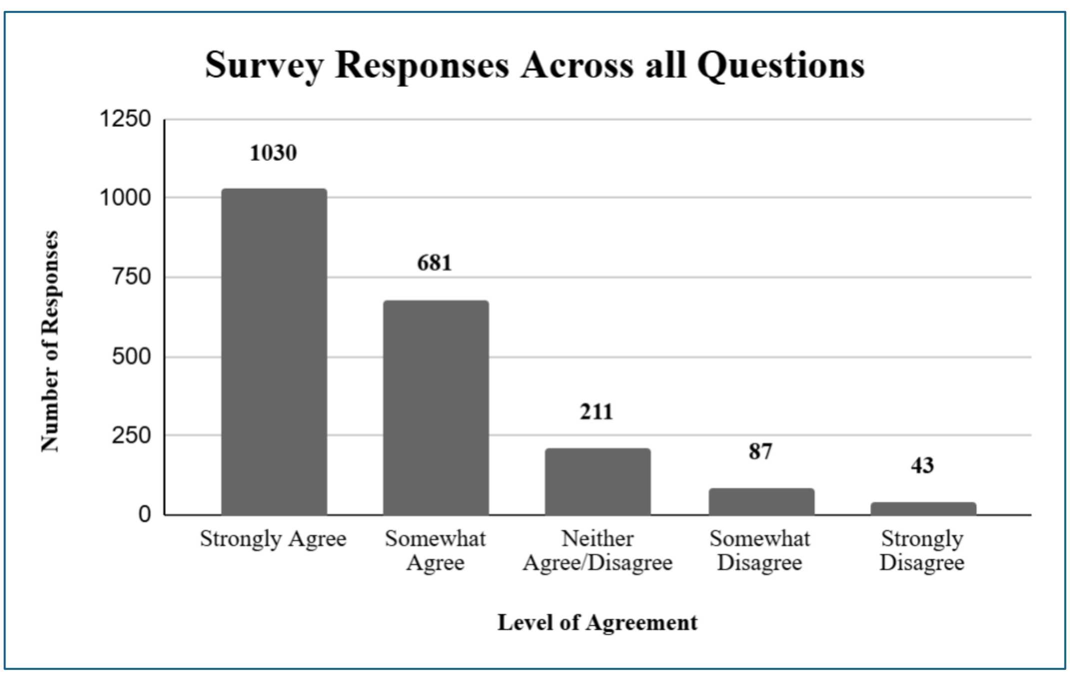

Figure 6. Total responses compiled with their agreement rates.

As each statement requiring an agreement rating was positively oriented, the upper and lower bounds of quality point normalizations based on our data analysis technique are 48 and 0 respectively. More directly: of the categories excluding short answers, student responses towards the general insight, clarity, satisfaction, outcomes, and collaboration statements were 80.7%, 78.7%, 88.6%, 80.7%, 90.9% positively oriented respectively (e.g. percentage responses of either somewhat or strongly agree).

A notable observation from the collected data is the slightly greater positive feedback in the pilot phase despite student suggestions being implemented for the finalized phase. The drastic sampling difference between the two phases may introduce a lack of repeatability within the pilot phase response set. For example, if one student responding "Strongly Agree" on all 12 questions is removed from the pilot phase set, the normalized quality point total becomes 39.06 (-0.21 points); we thus see a lack of stability in phase calculations, incentivizing analyses centralized on total responses.

In observing the total responses, the activity was assessed by the students to be highly beneficial. Participants felt a great sense of collaboration and satisfaction above all other categories; the outcomes of multidisciplinary learning were similarly achieved in a vast majority of students. From the short answer prompts, we interpolated approximately 75 students held constructing the mechanical components to be more favorable, while 29 students found circuit creation (more generally, breadboard construction and wire implementation) their favorite portion of the activity. The rest of the responses were either oriented towards enjoying the activity as a whole or specifically seeing how each portion meshed in the end.

A result beyond the original scope of our investigation consequently arises from these numbers: the separation of students enjoying the more mechanical-based versus electrical-based segments is similar to the percent difference of yearly mechanical and electrical engineering bachelor's degree recipients. According to the ASEE 2019 edition of "Engineering by the Numbers", the ratio of mechanical to electrical engineering bachelor's degrees awarded in 2019 was roughly 2.7 [3]. From our survey results, the ratio of mechanically to electrically favored student responses was 2.6 Thus, while the activity is intended to introduce students to multidisciplinary engineering (of which we see it successfully completes this objective), it may also serve to help students identify specific engineering fields they find more attractive or engaging.

Conclusions

The multidisciplinary engineering activity implemented in the Engineering Fundamentals course was highly successful, as evidenced by the overwhelmingly positive student feedback in both the pilot and finalized phases. The normalized quality scores, near the upper bounds on the scale, show that students found the activity engaging, clear, and beneficial. Regarding collaboration and satisfaction with the activity, high positive ratings are also shown. These results may indicate that the activity fostered a cooperative learning environment. This activity fits the learning objective of introducing students to multidisciplinary engineering settings. The different tasks require the integration of mechanical and electrical components that may help students be in contact with multidisciplinary engineering systems.

Furthermore, the mechatronic arm activity — while maintaining an important feature of modularity — particularly assists in student introspection, introducing an understanding of where personal interests lie early in student academic careers. It is through these avenues that we shed light not only on the benefits of mechatronics as a critical tool for multidisciplinary engineering education, but also on the necessity of such an invention towards the ever-changing landscapes current and future generations of engineers must adjust to.

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