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An Interdisciplinary Myoelectric Prosthetic Hand Capstone Project

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Abstract

Interdisciplinary capstone projects have been used in engineering education to provide students an opportunity to collaborate on a project with students from other disciplines that are different from their own. A few of the perceived benefits of such an experience are students developing a creative problem-solving approach, learning to communicate and collaborate with individuals outside of their major, increased understanding of the connections between different technical topics, and a deeper appreciation of other disciplines.

For the last three years, York College of Pennsylvania has conducted an interdisciplinary capstone project focused on designing and constructing a prosthetic hand that will interpret muscle contractions from a young amputee and output the desired movement in the hand and fingers. The overarching goal of the design was to create an affordable option compared to commercially available prosthetics as young amputees can quickly grow out of their prosthetic limb and are more likely to use a prosthetic that is visually appealing. Two features of the prosthetic design are myoelectric technology to detect muscle contractions and 3D printing technology in the construction of the hand. Each academic year, a new student team spends two semesters focused on improving the prosthetic hand design from the previous year's team. The student team was small consisting of no more than five students from the Mechanical Engineering, Electrical Engineering, and Computer Engineering majors.

This paper will detail the evolution of the interdisciplinary project from its first group of students who focused their efforts on researching and developing an initial prototype, due to working remotely because of the COVID-19 pandemic, to the current year's team concentrating on implementing sensors in the hand and refining the ergonomics of the existing design. The paper will also include student & faculty reflection and discussion of the faculty facilitation needed for such a service-based project and how engineering educators can consider implementing such projects into their programs.

Introduction

Interdisciplinary team-based projects in engineering education are an approach to experiential learning which can provide students with a diverse learning opportunity to work closely with individuals from different disciplines [1, 2, 3]. Some of the benefits of participating on an interdisciplinary team include unique solutions to solving complex problems [3], improves integration of ideas from different disciplines [4], and allowing students the opportunity to connect with their learning on a deeper level [5]. These experiences are similar to what students would encounter working in industry on a diverse team with people from different technical backgrounds [1, 2].

The paper details a multi-year, multi-team interdisciplinary Senior Capstone project focused on designing and prototyping a prosthetic hand design using myoelectric and 3D printing technology.

Course Overview

At York College of Pennsylvania (YCP), the Electrical, Computer, and Mechanical Engineering senior capstone projects span two non-consecutive semesters. This is due to the structure of the engineering course sequence at YCP, which includes three mandatory co-op work experiences that alternate with the academic semesters after a student completes their second year. The first semester of the Capstone project is in the second half of a student's third year during the Summer semester, and the second semester of the project is in the first half of their fourth year during the Spring semester.

The Engineering Capstone course objectives are for engineering seniors, operating in design teams, to apply principles of the design process to create a product or process to meet the needs of a customer. Projects may originate in industry, as a contest sponsored by a professional society, or in other venues. The design team, with the guidance of a faculty advisor, must plan, direct, conduct, and effectively communicate the results of the design effort through a professional engineering report and oral presentation. The design project will include material within and beyond the curriculum as well as technical and non-technical considerations. Design projects often result in a deliverable prototype. As part of the course requirements and assessment of the students in the course, each student must:

- Submit their engineering notebook weekly for assessment.
- Attend weekly project meetings.
- Provide evidence of completion of various design, construction, testing, and system integration milestones throughout the semester.
- Participate in and develop content for presentations and poster sessions.
- Submit a summative technical report describing their individual capstone project contributions.
- Maintain professionalism at all times when interacting with team members or faculty members.

Each Capstone project is structured differently depending on the scope of the project and the instructors who are overseeing the project. The main focus of the Capstone project in the Summer semester is project research, defining requirements & project goals, a completed design and initial testing of the subsystems. The Spring semester is focused on complete system integration of all the sub-systems and thorough testing to ensure a robust functional prototype.

Many of the previous and current capstone projects at YCP, such as the Radio Telescope, Formula SAE, and Drones, are interdisciplinary involving at least two engineering majors. However, most of these projects involve over ten students working on the same project in small sub-teams that are not community or service-based. The Prosthetic Hand project was proposed by an Electrical Engineering student who was also part of the student team during the first year of the project. The motivation behind the service-based project was to develop and prototype a prosthetic hand design that can be built by anyone with some “do it yourself” inclination and at a considerably reduced price. Similar prosthesis projects completed at an undergraduate level exist ranging from purely mechanical [6] to also including myoelectric technology [7, 8].

Two Capstone instructors, one Electrical Engineering faculty member and one Mechanical Engineering faculty member, oversaw the management of this project for each semester. At the start of each semester, there was a short informal onboarding process where students from the current team would meet the previous team members to go through the functionality of the prototype and other setup procedures. The current team also has access to the previous team’s entire digital documentation of the project through a shared Google Drive folder. There was no formal mentorship setup between the current team and the previous team as the students only overlap in one on-campus semester which is the Summer semester before the previous team graduates.

Prosthetic Hand Capstone Project

Currently, more than two million people are living in the United States with the loss of a limb and nearly 185,000 amputations are performed yearly [9]. The average cost of a prosthetic arm can be between $3000 and $100 000 [10], depending on the functionality of the device, the level of limb loss, and the amount of health insurance coverage. The motivation behind this capstone project is to create an affordable prosthetic hand option compared to commercially available prosthetics, as a young amputee can quickly grow out of their prosthetic limb and are more likely to use a prosthetic that is visually appealing. Two features of the prosthetic design are myoelectric technology to detect muscle contractions and 3D printing technology in the construction of the hand. The design process and results for each year of the project are described below.

Year 1

In the first year of the project (Summer 2020 - Spring 2021), the student team consisted of five students, two mechanical engineering majors, one electrical engineering major, and two computer engineering majors. The first semester of the project, in the Summer of 2020, was entirely online due to the COVID-19 pandemic. To allow for some initial design prototyping and experimentation for the semester, the electrical and computer engineering students were each given a kit of various electronics components and tools, and one of the mechanical engineering students was given a small 3D printer. The students focused their efforts on:

- Research & familiarization into 3D printing and different types of 3D printing materials.
- Research & initial design for the hand and finger actuation of prosthetics using gears, tendons, etc. Designing a custom model of the prosthetic hand in SolidWorks.
- Understanding how to measure and utilize electrical muscle signals. The muscle signal sensor chosen is surface electromyography(sEMG) due to its simplicity in applying the noninvasive device to the user.
- Developed a list of required microcontroller capabilities and selected the STM32G474RE Mixed Signal microcontroller [11] due to a team member's prior experience with using this microcontroller and it met the desired capabilities.
- Writing and testing preliminary software using the microcontroller for motor control for a split hook hand design.

The initial block diagram of the prosthetic hand system is seen in Figure 1.

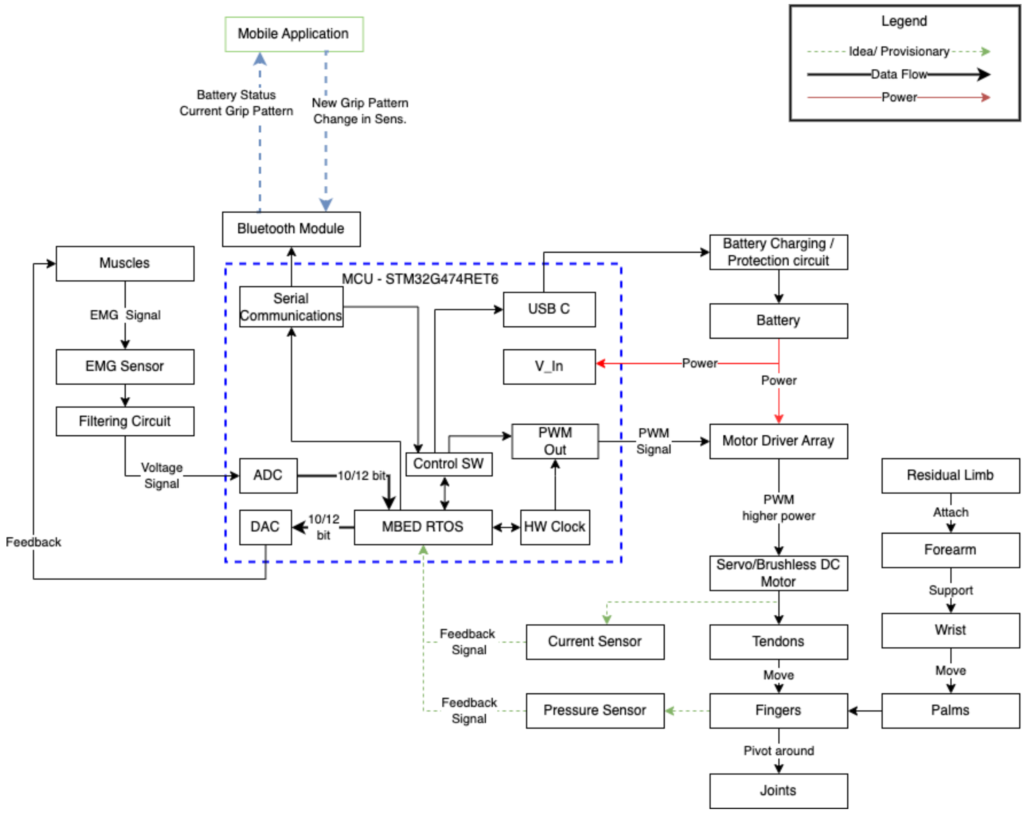


Figure 1: Initial block diagram of the system

In the Spring 2021 semester, the student team worked together in a hyflex classroom environment to complete the design and construct a functional prosthetic hand prototype. Hyflex learning is an instructional format that combines face-to-face and online learning. Every class session and learning activity that is offered face-to-face in a classroom is also offered synchronously for remote online students [12, 13]. Tools and resources are also set up in the course so remote online students can fully participate in the activities, discussions, and assignments as a face-to-face student would.

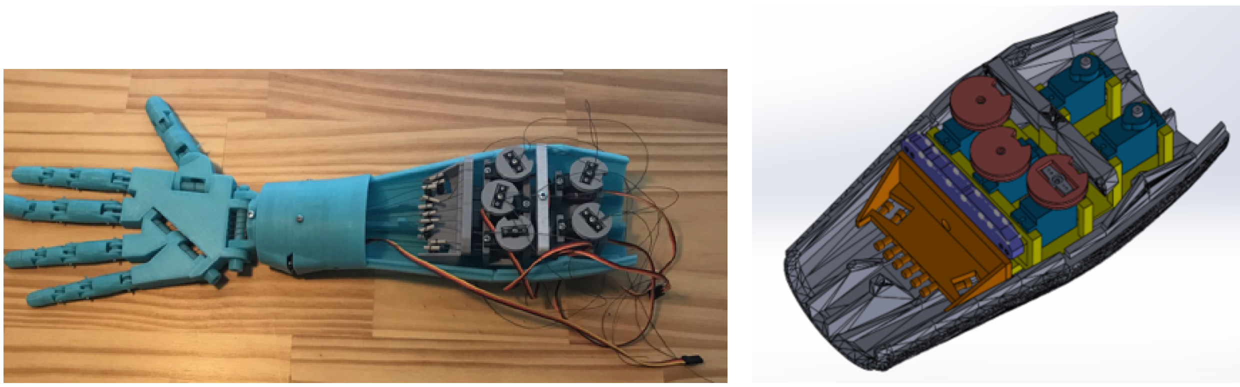
Due to limited time and resources, instead of using the design which was modeled in the prior semester, the team decided to start with a preexisting functional prosthetic hand design from InMoov [14] and make improvements iteratively. InMoov is an open-source website for a 3D-printed life-size robot that contains instructions and all the STL files used to build the robot. The InMoov hand and forearm was a two-tendon design utilizing two cables or tendons that when pulled would either clench or unclench the finger. Each finger was controlled by its own servo motor. The prosthetic hand was printed using PLA (Polylactic Acid) due to its strength, ease of printing, and low cost when printing out multiple prototypes. Several modifications made to the original InMoov design include:

- Redesigning the part in the forearm that the springs are attached to (called the tensioner) so there is less friction between the springs and tubing.
- Redesigning the cable router to accommodate the changes made in the tensioner. The holes are more spaced apart so that the cables align with the springs and limit interference with each other.
- The motors (Towerpro MG996R [15]) in the original design were replaced with small motors (RGBZone MG90s [16]) to significantly reduce the weight of the forearm design. This change also provided additional space in the forearm that could be used as a place for the electronics to fit in.
- As a result of using smaller motors, the servo motor bed and pulleys attached to the servos were also redesigned.

To improve the functionality of the electronic subsystems, the following design iterations occurred:

- Designed circuits to filter, amplify and transform the raw muscle signal data into data that can be readily used by a microcontroller. The circuits were also constructed onto a printed circuit board (PCB).
- Build and configuration of a reusable Linux-based development environment.
- Implementation of the servo motor control system and abstraction for easier interfacing with the user.
- Integration of FreeRTOS and related message passing protocols into the control system.
- Researched solutions to drive the servo motors and memory management on the MCU (microcontroller unit).
- Writing and testing code for servo drivers, ADC (analog-to-digital converter) data management, command handling, UART (universal asynchronous receiver/transmitter) communication, and data visualization.

Preliminary testing was completed on the integration of the prosthetic hand prototype and the servo motor control subsystem on the microcontroller. From the initial starting position, a servo motor was rotated until the finger it controlled was fully clenched. Then servo motor rotated in the other direction until the finger was fully unfurled. The servo motor controller setup was able to accurately control the position of all five servo motors by successfully clenching and unfurling their respective fingers. The movement of the fingers in the physical prototype was smooth but some of the cables would loosen after movement in the fingers. At the end of the Spring 2021 semester, the student team was able to get a functioning prototype with limited movement as the signal processing circuit was not yet integrated with the rest of the system. The final design that was constructed and its corresponding CAD assembly can be seen in Figure 2.



(a) Final Prototype

(b) SolidWorks CAD Model

Figure 2: Prosthetic hand prototype from Spring 2021

Year 2

The second iteration of the Prosthetic Hand Capstone project occurred during the 2021-2022 academic year. The student team consisted of five students and had the same makeup of majors as the last team consisting of two mechanical engineering majors, one electrical engineering major, and two computer engineering majors. Using the previous team's work as a starting point, the main tasks completed in the Summer 2021 semester were:

- Converting all the STL 3D printing files for the different parts of the hand to SolidWorks CAD files to allow for easier editing and modification of the components.
- Research into different hand grips and how to implement the thumb in a usable manner.
- Redesign the palm to create a more anatomically correct prosthetic that will also allow for a more natural actuation of any hand movement.
- Research into pins and bushing to reduce friction in the joints of the hand.
- Selected the MyoWare Muscle Sensor [17] as the myoelectric signal acquisition device. Electromyographic (EMG) data is gathered from the biomedical sensor pads adhered to a person's skin on the anterior forearm area just below the elbow joint.
- Writing and testing code on the microcontroller for data processing of the analog signal received from the myoware sensor.

The Spring 2022 semester was heavily focused on integrating all the subsystems to create a functional prosthetic hand that given a detected muscle signal there was finger movement in the hand. The following design changes occurred:

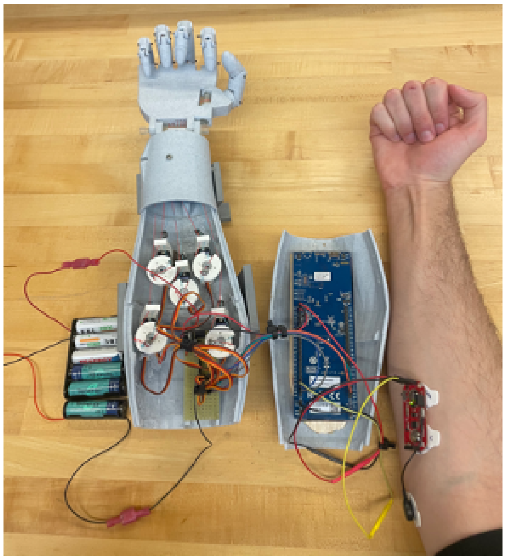
- Redesign the joints using slotted spring pins for each finger and palm joint to reduce friction in the joints while actuating the hand and eliminating the need for sanding during the assembly process.
- A power circuit was designed to have a power source of 6V or higher which supplied 5V and 3.3V to the servo motors and microcontroller, respectively. The power source was run off NiMH batteries to allow for the mobility of the prototype.
- New servo motors (HF-S8205MD [18]) were implemented into the prototype due to their high torque, small size, low weight, and low power consumption.
- Software in the microcontroller was written and tested for controlling the servo motors using a pulse width modulated output signal. Each finger was controlled was a separate servo motor and the amount of rotation of the motor is based on the size of the finger.
- Three thresholds level based on the output signal of the myoware sensors were selected to control when the hand moves between clenched & released positions. Once a threshold is reached, the servo motors rotated. The two upper thresholds control the speed at which the hand closes which is a faster speed for higher amplitudes and a slower speed for lower amplitudes.
- Muscle signal data using the myoware sensors was gathered from twelve human test subjects, with IRB approval, to create a robust working system.

The final prototype of the prosthetic hand, at the conclusion of the Spring 2022 semester, is shown in the clenched and released position in Figure 3.

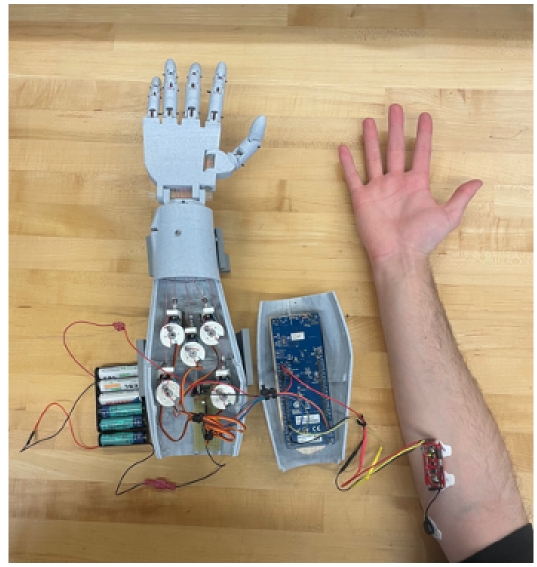
Year 3

In the third iteration of the project, during the 2022-2023 academic year, the student team initially consisted of three students with one mechanical engineering major and two electrical engineering majors. At the start of the Spring 2023 semester, another mechanical engineering student joined the team. The main focus for this year was to refine the previous design while adding sensors to the hand for increased feedback and control of the different hand motions. In the Summer 2022 semester, the main tasks completed were:

- Research and testing were completed on different feedback sensors. Force sensitive resistors (FSRs) were selected as the sensors are small in size so they can fit easily on a fingertip and their functionality allows them to detect an object without much difficulty.
- Redesigned the fingertips to integrate feedback sensors onto the hand. Also, tested different adhesive materials to attach the FSRs to the fingertips and the hand. Vinyl gloves were used in the final prototype due to their gripping ability and easier integration with the feedback sensor.
- Modified the lowest joints to increase their range of motion in the fingers.



(a) Clenched Position



(b) Released Position

Figure 3: Prosthetic hand prototype from Spring 2022

- Changed the servo motor placement to create more space in the forearm for future design changes.
- Gathered muscle signal data from two myoware sensors, placed on opposite sides of the arm, for ten different hand positions.
- The microcontroller was changed to the ESP32-S2 [19] as the previous microcontroller (STM32G474), implemented by the previous teams, had many unused features and took up too much space within the forearm.
- Redesigned the power circuit to include current sensors and a battery management system to prevent the servo motors from stalling and protects the power system. The power source was also changed to Lithium Ion (Li-Ion) batteries.

The Spring 2023 semester was focused on the complete system integration of the different subsystems resulting in a fully functional prototype of the prosthetic hand with feedback sensors. A revised block diagram of the system can be seen in Figure 4.

The areas that underwent design changes were:

- Created and implemented a new design for an opposable thumb.
- Selected and implemented new servo motors [20] that are position based up to 300 degrees rotation.
- Designed and constructed a printed circuit board for the microcontroller and power subsystem.
- Research and implemented a better adhesive option for the FSRs to the fingertips using rubber fingertip covers and a glove for the hand.

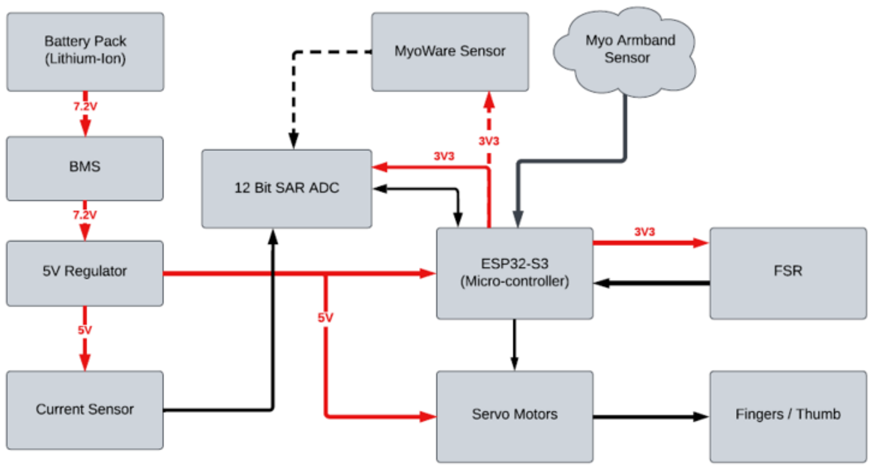


Figure 4: Revised block diagram of the system

- Implemented a different signal acquisition device through the use of the myoband [21] to allow for a wireless device to acquire muscle data.
- Implemented five different hand positions, which are platform push, large diameter, index finger pointing, adducted thumb, and tripod, based on the muscle signal received from the myoband sensors.

The final prototype of the prosthetic hand at the end of the Spring 2023 semester is shown in Figure 5. The prototype was able to pick up and hold a range of objects including a tennis ball, an 8-ounce water bottle, and an empty soda can.

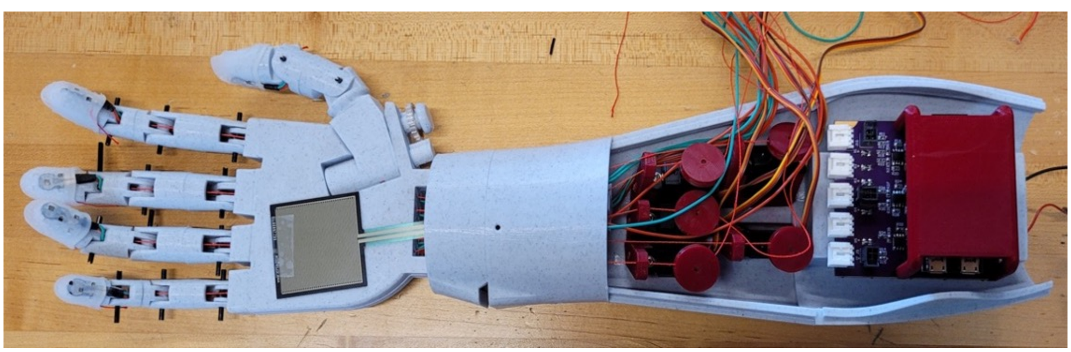


Figure 5: Prosthetic hand prototype from Spring 2023

Results and Discussion

The two Capstone instructors who oversaw this project wrote extensively on their experience with the facilitation needed for this service-based project as well as reflecting on the approach taken and any recommendations for changes. The students who worked on this project also provided feedback about their experience in their final presentation and summative technical report. Students specifically reflected on the lessons learned after completing this project and what they wish they would have done differently if they had a chance. The faculty and students' reflections specific to each year of the project are described below.

Year 1

In the first year of the project, the students and instructors recognized the challenges of working remotely for the first half of the project and then transitioning to a hyflex learning model. Establishing clear communication between all the team members early on in a project allows for less miscommunication. An instructor wrote: *In Summer 2020, it was initially difficult for team collaboration as the students would often work independently which was harder to coordinate their efforts. Although completing a Capstone project entirely remotely is not ideal, through this experience of online project-based learning the students became proficient in communication, online meetings, and presentations. As the semester went on, the students also took the initiative in setting up their own Zoom meetings outside of class to work on the project together. In the Spring 2021 semester, the entire team was able to be back on campus in a socially distanced manner. The students collaborated and physically worked together on campus in the engineering building in a more deliberate manner as they were fewer distractions compared to working from home.*

A student on the team has similar thoughts: *Working on a project like this during the COVID-19 pandemic creates a number of challenges. Particularly when it comes to working closely with teammates. Make sure to continually communicate to teammates what is being worked on. Communication between members within the electrical team is important, but remember to clarify with the mechanical team what the electronics are and aren't capable of. Don't assume teammates know or understand the specifics of what you're working on.*

Although the students were pleased with what they had accomplished during the first year of the project, the Mechanical Engineering students commented on how they would have liked to have spent less time in the research phase of the project and more time on designing and prototyping using preexisting designs. The Mechanical Engineering students wrote: *One of the biggest lessons learned was that the team should have focused less on research in the first semester and instead started construction of a design. If the mechanical team would have started printing and constructing a preexisting hand design earlier they could have had more time for improvements and more of an original design. Although the team was able to make a few of the improvements to the design they wanted, there were more redesigns and edits they were hoping to get to so the hand functioned more to their satisfaction. If the team was to do the project over, one thing we might have done differently would be to take greater design leaps. Larger changes or more simultaneous changes could have been made and tested. Another thing the team would have done differently is immediately start working on the preexisting design instead of attempting to create our own design from scratch. Time was lost trying to design our own prosthetic from scratch.* A rapid prototyping design phase using 3D printing to construct the physical prototype is feasible but can also be detrimental for a complex system, such as the prosthetic hand, as limited technical analysis could overlook better solutions and the rapid prototype might not be anywhere close in functionality to the desired final product.

Interestingly, the Electrical and Computer Engineering students had differing views and wanted to spend more time in the research stage before implementation to gain a deeper understanding of what they were designing. They wrote: *In terms of research and prototyping, it is important to start off small and build off small successes. Always start with a top-down view and then look to the bottom-up perspective. If you do not know what the purpose of your feature is, you will not understand how to integrate it into the rest of your project. Think about how you will test your feature before implementing it. Get comfortable with reading datasheets and library documentation, as this is the best way to gain a mastery of your platform and software.* The difference in approaches to the design process can be challenging for instructors on how to redirect those students who prefer a hands-on approach to building the design first as opposed to technical research and analysis before implementation. However, in an interdisciplinary project, sharing ideas and different approaches to problem-solving can create more unique creative solutions.

Year 2

Communication among team members was again another area that could be improved in the second year of the project. A Mechanical Engineering student wrote: *A lesson we learned was the importance of clear communication between teams. There were some issues when one team failed to communicate the requirements of the system to the other teams. We were finalizing the hand and I had calculated estimated degrees of rotation for each finger, then gave those numbers to another student but failed to let him know they were estimates. If I had let him know that the numbers were subject to change more progress could have been made that night.*

Sometimes getting students to communicate and work more closely with one another requires intentional efforts from the instructor to establish team member expectations. This is especially important on an interdisciplinary team where students initially might not know each other and are hesitant to provide feedback on areas outside their technical expertise. One of the instructors wrote: *During the Summer of 2021, this team of students worked mostly independently from one another, and they would often not know what another team member was working on. During the Spring 2022 semester, I intentionally ensured there was more cross-collaboration between the ECE and ME students. Each ECE student was paired with an ME student to work on a specific sub-system of the project together and the students were told to regularly check in with their partner throughout the project to discuss what each of them was working on. This proved to be effective as the students developed better team dynamics and fostered a more collaborative work environment.*

Another common ”theme” learned by all the students, during this iteration of the project, was the importance of checking your work and ensuring proper research is done before proceeding to the next step in the design process. Below are some of the students’ self-reflections related to this:

- *At the start of this semester, we had weak, unreliable, and inconsistent signals from the muscle due to the arbitrary placement in the center of the forearm. We spent a lot of time trying to improve this reliability in code and trying many different sensors. What we should have done is started off by researching the best muscle in the forearm for attaching electrodes. Once this research was done, we were able to get consistent reliable signals. The time spent researching this new muscle was much less than the time spent in trial and error trying to find the best spot on the forearm to place the electrodes and would have* *saved us a lot of time if we had started off with researching this.*

- *During testing, my team member and I ended up with a smoking capacitor in the circuit, which at the time, I did not know why it happened. Doing some research over the following weekend, I educated myself more on capacitors and discovered that there is a third type of capacitors, and that, like electrolytic capacitors, tantalum capacitors are polarized. I believe this to be the most likely reason behind our smoking capacitor. Afterward, the tantalum capacitors were replaced with electrolytic ones, being careful to observe the polarity.*
- *We learned the importance of double-checking the dimensions and tolerances to verify that everything will fit together correctly. After the conversions of the parts from one format to another, the team never verified the dimensions of the new parts. This caused some problems with the assembly of the new hand. The first hand that was printed took over six hours to assemble since a lot of sanding needed to be done to fit it together. This lead to a lot of friction and the inability to actuate the hand.*

It is not uncommon for students when working on a team project to recognize the need for due diligence and attention to detail in their work. In Capstone projects, this learning experience can routinely occur as the students are the ”experts” of the project so they are the ones that need to ensure everything is working before moving on next step. Students are given the freedom to work at their own pace and this usually occurs independently of an instructor being present. The instructors in a Capstone course typically serve in a ”project manager” role to ensure deliverables and deadlines are met but they may not be as familiar with all the technical details in every aspect of the project.

Year 3

In the current year of the project, the students reflected deeply on the development of the team dynamics throughout the Capstone process.

- *In this project, I feel like I learned how to better work with and understand my teammates. In past team projects when work was distributed to each member, we performed it independently of each other without much overlap. However, in this project, it is nearly impossible to do much work without consulting our teammates as everything must work together physically instead of just on paper. Overall, I am very happy with how this project went. Each member of the team put forth a good amount of effort to ensure all our goals were met on time. Everyone took time to work together and assist each other when one of the team members ran into an issue. Each member took the time to make sure everyone was on track and that any work they were doing would not interfere with that of another. I have no complaints about our team dynamics and believe we found an optimal dynamic between the three of us to ensure productivity while also enjoying the process of working together.*
- *Working in a team on this capstone project has taught me that everyone has their strengths and weaknesses within a team. This also means everyone has different background knowledge, so it sometimes takes more time for some team members to grasp different concepts. Something our team did is set two times a week to meet outside of class. This was very beneficial and will be continued into next semester because it allowed our team to*

> *have specific times where we were all working on capstone together instead of fitting in times only by ourselves outside of class and homework. Working in a team takes a lot of patience and cooperation, which is something I have learned over the past few years in the engineering program. There are many times when you and/or your teammates are stressed, and this can be taken out on the team, so it is important to be able to stay calm and collected in harder situations, even if a teammate isn't.*

One of the instructors was also able to observe the improved team interactions with this particular group of students: *Although this team was slightly smaller in size, compared to the two previous years, the students on the team get along and work very well together. I have seen the entire team in the project room, consistently throughout the semester, brainstorming solutions to issues that affect more than one subsystem and performing testing on the prototype without any faculty direction or assistance. This is a very different team dynamic compared to previous teams who required more intentional instructor guidance on team communication.*

One potential explanation as to why this team of students had more effective communication and team dynamics is some of the students had previously worked together on engineering projects. The two Electrical Engineering students had been part of a multi-week group project in their engineering design course in their third year. Also, one of the Electrical Engineering students and one of the Mechanical Engineering students had worked at the same company during their second co-op and had their office cubicles next to each other. Since some of the students had already developed relationships of trust and were comfortable with each other it was a lot easier for them to share ideas, provide feedback, ask for help, and work collectively.

Conclusion and Future Work

The current plan for this project is to conclude it at the end of the 2022-2023 academic year as there are only a few design issues remaining which would not require an entire interdisciplinary student team. There are a few smaller areas of research that could require a discipline-specific student to work on, through an independent study, such as a Mechanical Engineering major working on the actuation of the thumb or the attachment mechanism to the amputee.

This work can be extended to include not only other engineering disciplines such as biomedical engineering, structural engineering, and manufacturing engineering but other majors outside of engineering such as computer science, nursing, physical therapy, etc. Due to the structure of the engineering course sequence at York College of Pennsylvania, extending this project to include other majors can be difficult as only Mechanical Engineering, Electrical Engineering, and Computer Engineering have the same senior Capstone semesters, which are the third-year summer and fourth-year spring. The Civil Engineering program at YCP has its Capstone project during the students' fourth-year spring and fourth-year summer. Also, the first semester of senior Capstone at YCP is completed during the Summer semester when the rest of the institution is not normally in session so external resources and faculty/staff support from other programs can be limited. Curriculum changes to the engineering programs are currently occuring to help mitigate some of these challenges.

The instructors of this capstone project, plan to continue to offer interdisciplinary service-based senior Capstone projects. This project could always be completed again in future years of

Capstone without providing the student team with any of the existing documentation from past student teams and see what they come up with. Interdisciplinary projects provide both students and faculty an opportunity to work with those outside their major which can lead to creative problem-solving approaches and unique design solutions.

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