COMPACT ROBOTIC WRIST AND GRIPPER USING STEWART PLATFORM GEOMETRY

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ABSTRACT

This project addresses the limited dexterity of parallel jaw grippers on the Rethink Robotics Sawyer robotic manipulator by integrating a 6-degree-of-freedom (DOF) Stewart platform with a parallel gripper. The resulting mechanism replicates the complex motion of a human wrist, enabling precise manipulation in tasks requiring multi-axis motion. The design utilizes six Actuonix L12 linear actuators configured in a 6-6 Stewart platform geometry, with aluminum base and top plates connected to the actuators via universal joints. A 3D-printed parallel jaw gripper is mounted on the motion plate for grasping objects, e.g. a tennis ball. Rigorous kinematic, inverse kinematic, dynamic, and FEA simulations were conducted in Siemens NX to validate the concept and ensure mechanical integrity. A Faro Arm was used to verify the system's compliance with specifications. The prototype achieved rotational capabilities exceeding 30° about the x and y axes, over 60° about the z-axis, and translations of at least 3 cm in the x, y and z directions. The assembly successfully lifted payloads of at least 0.8 kg, remained within dimensional constraints (14.94 cm height, 8 cm diameter), and maintained a total mass of 0.674 kg. These results confirm the design meets all requirements and specifications, offering a viable solution for enhancing robotic dexterity and possibly broader applications.

PROBLEM DEFINITION

Parallel jaw grippers for the Sawyer Robotic Manipulator lack the degrees of freedom to replicate the motion and flexibility of a human wrist. This project focuses on combining a 6 degree of freedom (DOF) wrist joint using a “Stewart Strut” platform and a parallel gripper. The Stewart platform’s unique geometry allows for translation and rotation of a motion plate about any point in space. By attaching a parallel gripper to the motion plate of the platform, a complete hand and wrist mechanism can be created. This problem is important to Professor Thomas Howard, who is interested in such a device to interface with the Sawyer Robot. The Sawyer is designed to perform tasks working alongside humans. By achieving more human-like movements with Sawyer’s robotic arm, the robot’s ability to carry out human tasks can be improved. The project will be carried out in conjunction with an ECE design team for the electronic and programming aspects of the device.

REQUIREMENTS, SPECIFICATIONS, DELIVERABLES

Deliverables:
- CAD Model
- Kinematic Model
- Structural Analysis
- Stewart Platform Subsystem
- Gripper Subsystem
- Electrical Subsystem
- Metrology
- Test Data

Requirements:
- Motion plate must exhibit motion in 6 degrees of freedom.
- Mechanical system must interface with the Rethink Robotics Sawyer Platform.
- Design must allow power and signal wires to pass through uninhibited hexapods.
- Grippers must be able to grasp and hold a tennis ball.
- Must enclose MCU, motor controllers, voltage regulators and interfaces.
- The gripper must be interchangeable on the motion plate.

Specifications:
- Minimum translation in the x, y, and z coordinates in the base frame of 3 centimeters.
- Minimum rotation about x and y coordinate axis in the base frame of 30°
- Minimum rotation about the z coordinate axis in the base frame of 15°
- Maximum device height (cylinder envelope excluding the gripper assembly) of 15 centimeters.
- Maximum device diameter of 8 centimeters.
- A minimum payload of 0.5 kilograms to be held securely by the gripper.
- A maximum mass of the whole assembly (platform and gripper) of 2 kilograms.

To provide additional context and support for the work completed over the course of the semester, Figures and Tables located in the Appendix offer visual and structured representations of key elements of the project. Figure 1 presents

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a Work Breakdown Structure (WBS), developed to divide the project into manageable tasks aligned with the semester timeline and deliverables addressed earlier in this section. Furthermore, Table 1 provides an overview of how each design specification was evaluated and validated. These requirements, deliverables, and specifications confirm performance across the Stewart platform, gripper, and electrical subsystems.

CONCEPTS

Table 2 shows a Pugh matrix of the different Stewart Platform setups considering the range of motion, stress experienced, ease of manufacture, and cost. Although the Type 3-3 experienced less stress than Type 6-6, the Type 6-6 would be less expensive and significantly easier to manufacture as connecting actuators together would be much more difficult than attaching them individually to a plate. The ease of manufacturing advantage of the Type 6-6 and its lower cost meant that the Type 6-6 won the Pugh Matrix and was our choice of model setup.

Figure 2 shows three different hexapod models where three different actuator models were used. The left picture is a model using the P8 actuators, which have a 25mm stroke length. This means that it can't satisfy the translation in the z-axis, but it does not break any space envelope constraints. All other translation and rotation specifications would be met. The middle picture is a model using the L12 actuators. The L12's have a 30mm stroke length, meaning that the translation in the z axis would be very close to meeting the requirement. The model would pass all other translation and rotation specifications, but would likely not meet the space envelope requirements, breaking it in the height constraint. The L12's also have feedback and are the only model of the three actuators which have feedback. This is a big bonus for controlling the actuators as much more precise points in space can be controlled and attained. This is clearly a big advantage in a robotic setting. Finally, on the right is a model using the P16 actuators. These have a stroke length of 50mm and will meet all translation and rotation requirements but would break the height constraint of the space envelope. Table 3 shows a detailed comparison of these three actuator models which are being considered.

Table 4 shows a Pugh Matrix used to decide which actuator model the project would proceed with. The matrix accounted for many factors and concluded that the L12 actuator won.

Another important decision that had to be made was whether to use ball-joints or u-joints to attach the actuators to the top and base plates. The advantages of the ball-joints are that they have more range of motion than u-joints (360°) and their loads are spread across the entire surface which would result in less reaction force being transmitted to the actuators. The advantages of the u-joints though are that they take up much less space than the ball-joints, which is very important for meeting space envelop specifications, and they prevent rotation of the actuators. With the ball-joints, the actuators would be free to rotate, and nothing would stop them unless another component was added. Overall, the smaller space that the u-joints took up compared to the ball-joints was the deciding factor because the space envelope specification must be met.

After deciding to use U-Joints for both the top and bottom plates, an issue became clear that the platform would not be able to move if both sets of U-Joints were fixed to their respective plates. To solve this issue, the top plate U-Joints were connected to shoulder bolts which were free to rotate within brass bushings press fit into the top plate (Appendix B, Figure 3). This enabled platform movement while keeping a secure connection between the actuators and top plate. The top plate was also designed to be a smaller diameter than base plate to help increase the tilt of each actuator, reducing the force needed for translations and rotations of the top plate (Appendix B, Figure 3). Four holes were added at the center of the top plate to enable secure connection to the gripper as well as a larger center hole to allow the gripper servo's cable to pass through the platform uninhibited.

To satisfy the strict height constraint for the platform, custom connectors for the top and bottom of the actuators were designed. For the top of the actuators, this meant creating an M8 threaded insert with a small M3 pin on top of it for the U-Joint. The insert could be screwed directly into the top of the actuators replacing the plastic cap that comes with them. For the bottom of the actuators, a more complex U-shaped connector was designed which fit around the bottom plastic extrusion of the actuator and was secured with a bolt and locknut (Appendix B, Figure 4). This connector then included a circular sleeve for fitting on top of the bottom plate U-Joints and a hole for a M2 screw to pass completely through the U-Joints.

The base of platform underwent several iterations. The final design settled on using press fit dowel pins to secure the lower U-Joints. However, upon merging the device CAD with the ECE's PCB, it was found that there would be interference between the actuators and some of the PCB components. To solve this, the U-Joints were propped up with spacers above the base plate and longer dowel pins were selected (Appendix B, Figure 4). Additionally, to allow easier attachment and removal of the device to the Sawyer robot's tool plate, two separate base plates were designed; one to connect directly to the sawyer and another to hold the rest of the device including the U-joints and PCB. These plates were connected with three extruded blocks on the Sawyer base plate, matching cutouts on the platform base plate, and M3 socket screws (Appendix B, Figure 4).

For the parallel gripper, a simple modular design with track sliding arms was settled on. This included two flat faced arms which were moved on a track by a singular servo and gear (Appendix B, Figure 5). After an initial design and prototype was tested, it was found to be too large and heavy for the Stewart Platform. Because of this the body was redesigned to fit as closely to the servo as possible to reduce the size of the gripper and save weight. All three sections of the gripper body were

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connected by two long M4 screws. Holes for 4 M3 screws were also made into the body base to connect to the top plate of the platform as well as a hole for the servo cable to pass through the top plate to the PCB (Appendix B, Figure 5). Each component of the gripper was designed to be able to be easily 3D printed.

MECHANICAL ANALYSIS

Tolerance Analysis:
The mechanical wrist assembly is one composed of many parts such as bushings, screws, and pins with the main purpose of connecting the different components into a single body of motion. Tolerance is critical as they ensure everything fits and works as intended without causing any performance issues. It tends to be one of the first things to be analyzed because they determined the manufacturing processes and the cost of the parts and operations.

One of the most crucial tolerances determined in the assembly is the dimension between the diameter of the hole of the base plate and the outer diameter of pin that connects this plate to the universal joints (Figure 3 in Appendix). As the function of the pin in this occasion is to be fixed, an interference fit is applied (ISO System: H7/p6) [Reference of lecture 0400 ME 205 Metrology Tolerancing]. Therefore, the outer diameter of the base plate's holes has limits of 3mm (+0.002"/+0.000"), while the pin outer diameter [Fig. 4 in the Appendix] is 3mm (+0.008"/+0.002").

Another essential tolerance added was in the top plate between the inner diameter of the bushing and the outer diameter of the should screws that behave as a pin. In this case, the functionality needed from the shoulder screw is to rotate freely inside the bushing to not constrained the actuators from moving. Therefore, a sliding fit (ISO System: H7/g6) was added where the bushing inner diameter [Fig. 5 in Appendix] has dimensions of 3mm (+0.02"/+0.00") and the shoulder screw outer diameter [Fig. 6 in Appendix] is 3mm (+0.000"/-0.025").

Fastener Torque Analysis:
Another important analysis for manufacturing and assembly is determining the optimum torque to apply to fasteners. One crucial fastener is the M3 socket screw used to fasten the two base plates together. There are three of these screws which handle the loads of the entire assembly above them and are essential for making the device mountable on the Sawyer Robot. An analysis of one of these fasteners is included in Appendix A, Figure 15. The analysis uses the material properties of the screw, it's surface finish, and its dimensions to determine the optimal torque to fasten the screw with. This came out to 1.053 N*m. This torque will be used to fasten the plates together so they are secure but aren't over tightened.

Fatigue Analysis:
Even with a properly assembled device that operates correctly and smoothly from the offset, over time, fatigue can lead to component failures and the need for replacing one or many parts to return a device to operation. The U-joint block pins are one of the smallest moving components on the device and experience the direct loads of the platform. A fatigue analysis was carried out for these pins to ensure that they would not fail from cyclical loading and can be seen in Appendix A, Figure 16. The analysis including determining the maximum stress on each pin using a finite element model and computing the Marin factors for adjusting the ultimate strength of the pins. Using both the Soderberg and Modified Goodman methods, the pins satisfied the criterion for infinite life, meaning no number of cycles will cause structural failure of the pins.

Material Selection:
Using aluminum and brass for the construction of a Stewart strut offers a significant advantage over 3D-printed plastics in terms of mechanical performance and durability. Aluminum alloys, such as 6061, have a tensile strength of around 290 MPa and a Young's modulus of approximately 69 GPa. Brass, often used in bushings and low friction interfaces, offers similar benefits with good machinability and a typical tensile strength around 350 MPa. In contrast, common 3D-printed thermoplastics like PLA or PETG have much lower tensile strengths (50–70 MPa) and moduli (2–3 GPa), making them unsuitable for precision mechanisms under stress or repeated motion. Additionally, metals maintain dimensional stability and resist creep and deformation over time—critical for Stewart platforms where accurate positioning and motion translation are key. Therefore, all machined parts such as the top plate, bottom plate, Sawyer connection, connecting blocks and pins were machined out of metal as all these parts are crucial for the platform, while other key components such as the universal joints and bushings were selected to be out of brass and oil embedded copper respectively. Other components such as the gripper itself, were 3D printed as they are not subject to repeated movement under high loads.

FEA Models:
Figures 7-10 show different FEA models which were solved in order to determine the differences and the best model setup type for the hexapod. There are four different types: Type 3-3, Type 3-6, Type 6-3, and Type 6-6. They are differentiated by how the actuators are connected. If the linear actuators are connected to one another at the top and bottom plates then there will be only three connections on each plate (Type 3-3), and if they are individually connected to each plate then there are six connections to each plate (Type 6-6). Type 3-6 and Type 6-3 are combinations of each of these. The FEA simulations modelled the actuators constrained to the base plate in SPC123, and had an RBE2 connected at the top (constrained with SPC 123) to distribute the force of 1.5 x 9.81 N. The purpose of these four FEA models was to determine the max stress experienced through the actuators in each model setup type and to compare the differences. The setup experiencing the lowest stress would be the optimal design, but other factors have to be considered, such as ease of manufacture and cost, which can be seen in Table 2. The results of the FEA models, shown in Table 5, showed that

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Type 3-3 experienced the lowest stress, followed by Type 6-6.

Cantilever Beam:
Figure 11 in Appendix shows a cantilever beam analysis produced to analyze the bending and shear stress acting on the dowel pins which the u-joints sit-on. This is an important calculation because having thin dowels which support all of the weight and force passing through the actuators could be subject to high bending and shear stress. The calculation uses an over-estimate for the force that could be passed through the actuator to the dowel pin (1.5kg x 9.81N/kg) to be safe. In reality, the force passing through a singular actuator and to each dowel pin would be much less than this because the force would be split among the six actuators. However, the dowel-pins still passed under both shear stress and bending stress. Under bending stress, the pins passed with a FOS of 35, and under shear stress they passed with a FOS of 1952. Clearly, both FOS are more than sufficient and there is no need to make any adjustments to the design.

Dynamic Model:
Figure 12 shows a dynamic model of the system to assess the forces experienced by the actuators and the base at different orientations. This is important because before purchasing the actuators and building the system, it must be known that the actuators and system can withstand any potential forces they may be put under so that the system does not fail, and money is not wasted. This dynamic model has a 1.5 x 9.81 N force applied, which is the maximum possible force that could be experienced from the specifications. This force was applied in the y-direction as this would cause the "worst case scenario" for the actuators. The system was run with a harmonic motion so that all possible orientations could be covered. Figure 12 shows a model where the speed was constant, and the phase was changing. The model experienced a maximum force of approximately 2.5N at the base. This is a positive sign because the L12 actuators are able to withstand 22N, so this doesn't come close to their force specification. In the second dynamic model, shown in figure 13, everything was kept the same except for now the speed and phase were both changing. This caused a lockup position where a force of approximately 14N was experienced on the base. This should still be ok because it is still less than the maximum force that the L12 actuators can withstand, but it's important to make a note of lockups and write a code to avoid these orientations to prevent failure. This is especially important because some lockup positions may have forces which are higher than the actuators can withstand, so it could cause them to break if the lockup position isn't addressed.

MANUFACTURING

For the construction of the Stewart strut, our team divided the machining tasks across smaller groups to efficiently manufacture five distinct components. A team member was responsible for the HAAS CNC code in Siemens NX for the Sawyer Plate. Another one, took on the Connecting Block, also developing HAAS code in NX to create a robust link between strut elements. A third one, focused on crafting the Connecting Pins using the manual lathe, a task requiring close attention to tolerance and finish for proper fit and motion. Meanwhile, the last team member handled both the Top and Bottom Plates, using a combination of CNC ProtoTrak and manual milling to balance speed and adaptability in the machining process.

In parallel with the machined components, the team also developed a mechanical gripper that would be integrated into the system. A first version was designed and 3D printed, providing a functional prototype for initial testing and fitting. Based on that feedback, a second version was created and improved, and 3D printed, which offered enhanced geometry and reliability. This iterative design approach allowed for rapid prototyping and optimization while the core structure was being machined.

All in all, this process took several hours to both design and manufacture as seen in table 2 and table 3 with a cost of $46,270 assuming a rate of $100/hr. over four months (January-April). In addition, for this cost, there is also the cost of all the material and parts bought, as shown in Table A, which had a cost of $953. Altogether the final cost of the project is estimated to be $47,223.

The estimated cost is for a single device designed and manufactured from scratch. However, if this project were to be scaled as to manufacture hundreds of them, different technics could be used to lower the cost. For instance, all the plates could be casted, reducing the time for a part to be made greatly and therefore the cost of it too (excluding cost of the mold). Similarly, the pin connectors could be automated with CNC code and perhaps a small assembly line that is only focused on producing those parts by the hundreds, if not thousands, reducing the cost. Also, the actuators' cost could be reduced. Most of the material cost comes from buying the actuators and given the quantity of actuators to be bought and way to reduce the prices can be reached.

TABLE A: BILL OF MATERIALS

Material	Company	Price
7x L12-I 30mm Actuator (50:1 12V)	Actuonix	$720
3x 6 PCs M3 Universal Joint	Amazon	$27
Threaded Rod (M8x1.25mm)	McMaster	$11.71
6x Shoulder Screw (3mm x 6mm Long)	McMaster	$31.36
6x Oil-Embedded Bushings (3mm D, 4.5mm ID x 3mm Long)	McMaster	$97.09
4x Flat Head Screw (M6 x 8mm Long)	McMaster	$9.25
6x Socket Head Screw (M3 x 16mm Long)	McMaster	$7.09
4x Heat-Set Inserts (M4 x 7.9mm Long)	McMaster	$12.79
2x SS Flat Head Screw (M4 x 30mm Long)	McMaster	$10.63
6x Hex Nut (M3 x 0.5mm)	McMaster	$4.73
Aluminum ½" Thick, 8" x 8" Sheet	McMaster	$38.73
Aluminum 0.19" Thick, 6" x 6" Sheet	McMaster	$12.20
Aluminum 5/16" Thick, 6" x 6" Sheet	McMaster	$13.91
6x Spacer (6mm OD, 8mm Long)	McMaster	$12.30
6x Pin (3mm D, 18mm Long)	McMaster	$16.44
6x Spacer (4.5mm OD, 5mm Long)	McMaster	$2.00

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Aluminum Bar (½” x ½” x 2 ft)	McMaster	$4.00
Total		$953

TABLE B: MANUFACTURING TIME

Team Member	Time	Price ($100/hr)
Member #1 T	54.8 hours	$5480
Member #2 G	56.7 hours	$5670
Member #3 L	15.6 hours	$1560
Member #4 A	63.7 hours	$6370
Total		$19080

TABLE C: DEVELOPMENT TIME

Team Member	Time	Price ($100/hr)
Member #1	51.2 hours	$5120
Member #2	61.3 hours	$6130
Member #3	104 hours	$10400
Member #4	55.4 hours	$5540
Total		$27190

TEST PLAN AND RESULTS

After research was conducted on the actuators available in the market, it was concluded that, to meet the specifications for translation, tilt, and twist, the space envelope—specifically in height—would need to be exceeded. This proposal was presented to the sponsor, and an agreement was reached to modify the height specification from 10 centimeters to 15 centimeters. This change also enabled the enclosure of the electrical components used to control the Stewart strut platform within the platform itself, without causing interference with components such as the universal joints and actuators.

Before test data was obtained, the mechanical system was assembled (Figure 1 in Appendix D). Although the electrical and computer teams were responsible for controlling the Stewart platform, a simple control system was developed to collect preliminary test data. This system involved controlling each actuator using an Arduino and a power supply. A control code was created to operate the actuators through an interfacing linear potentiometer, as shown in Figure 14.

The Quantum X FaroArm® located in Hopeman 121 (within the University of Rochester Mechanical Engineering Department) was utilized to scan the assembly and measure displacements relative to the base coordinate axis, ensuring accurate data collection. Prior to scanning, spacers were placed between the table and the assembly to eliminate calibration errors during testing. The system was calibrated by measuring four points on both the base and top plates to define the base coordinate planes. The Stewart Strut platform was then moved to its extreme positions by controlling the actuators in order to capture the system’s maximum range of motion. At each of these positions, the top plate was scanned using the same method employed for the base coordinates. Data was collected by measuring the distance or angle between the reference plane (at the zero position) and the planes corresponding to translated, tilted, or twisted configurations.

Following the testing process, it was concluded that the system fulfilled all specified requirements. The test data is presented in Table 6. One important consideration related to the data is that the Z-translation was rounded to three centimeters, aligning with the precision defined in the specifications. It was also confirmed in agreement with the sponsor during the selection of the Actuonix L12 actuators that a Z-translation equal to or greater than three centimeters would be physically unachievable due to the platform's geometry, as the maximum stroke length of each actuator is limited to three centimeters.

The testing conducted for the Stewart Strut-based 6 degrees of freedom wrist joint system was primarily aimed at validating whether the constructed prototype satisfied the required specifications for translation, tilt, and twist. Although the test procedure involved controlled actuation and positional measurements using the Quantum X FaroArm®, the tests were limited in scope and did not incorporate statistical replication or multiple trials for each configuration. To improve the reliability and accuracy of the results, it is recommended that future testing includes multiple repetitions for each actuator condition, followed by statistical analysis of the positional data. Incorporating a greater number of trials would allow for the calculation of mean values, standard deviations, and confidence intervals, offering insights into the repeatability and precision of the platform. Additionally, alternative validation methods, such as motion capture systems or high-precision displacement sensors, could be employed to complement FaroArm measurements and cross-verify data accuracy.

INTELLECTUAL PROPERTY

The design of the device is patentable but a more thorough search for existing patents should be conducted, especially as some similar designs are in different languages and are difficult to understand. It does not seem that there is another design which is designed to connect to the end of an existing robot, uses six linear actuators which are connected via u-joints to the base and motion plate, and has its own parallel jaw gripper attached to the motion plate.

1st Similar Patent Number: DE102022110140B4
Title of and issue date of 1st similar patent: CONFORMAL PRESENTATION OF PAYLOAD BY A ROBOT SYSTEM WITH COORDINATED SERIAL AND PARALLEL ROBOTS. 2024-04-18.
Top 3 companies that file patents in the major classification area of this patent: 1. 北京猎户星空科技有限公司 2. Kuka Deutschland Gmbh 3. Fanuc Corporation

2nd Similar Patent Number: CN104390612B
Title of and issue date of 2nd similar patent: Six-degree-of-freedom parallel robot benchmark pose scaling method for Stewart platform configuration. 2017-03-08.

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Top 3 companies that file patents in the major classification area of this patent: 1. Here Global B.V. 2. Garmin Ltd. 3. 北京信息科技大学

SOCIETAL AND ENVIRONMENTAL IMPLICATIONS

In terms of safety, this project has a minimal level of risk associated with it. Most of the system is safe; the only potential risks could be getting a finger trapped when the actuators are moving and any potential to get an electric shock associated with the electrical side of the system. These risks have been reduced though, as the current has been limited to a safe level, and the actuators can be turned off if they sense too large force resisting against them e.g. a trapped finger. Furthermore, a sleeve will be placed around the whole actuator set-up on Design Day so that hands can't be placed in dangerous areas.

In terms of the environmental impact, this project has some negative implications which stem mainly from the materials and manufacturing processes used. The aluminium used for the top and bottom plates, while recyclable, requires high energy input for extraction and processing. The use of PLA for the 3D-printed is more environmentally friendly, as it is biodegradable and derived from renewable resources, but still requires energy in processing and this energy could come from non-renewable sources. Furthermore, many of the machining processes used—such as milling, lathe work, and drilling—consume significant electricity and generate material waste in the form of metal shavings and offcuts. Additionally, the use of coolants and lubricants in machines like the HAAS CNC lathe and the ProtoTRAK mill can be harmful if not properly managed. To reduce the environmental impact, future improvements could include optimizing part designs and the size of their raw stock material bought to minimize waste. Also, looking to use more additive manufacturing where possible, sourcing recycled aluminium, and ensuring responsible disposal or recycling of waste materials and fluids would further contribute to reducing the environmental impact.

Related benefits of this project and its technology stem from the problem definition and the purpose of this project. There are very few, if any, robots that have wrist-like motion and full 6-degree of freedom movement. This project educates and provides research into this problem and opportunity and allows people to learn about the possibilities of robotic arms and Stewart platforms. This could have potential uses in the medical or prosthetic industries, potentially providing new solutions and improving the lives of many.

RECOMMENDATIONS FOR FUTURE WORK

In terms of manufacturing, there could be an improvement on the way that the sawyer plate and bottom plate are manufactured and assembled. A suggestion to improve the process is to machine each of the two parts profile individually first (no side holes to connect them). Then make sure they fit together properly and make a boss to hold both pieces together through the middle hole they both have. Once that is done, they can be machined as an assembly. First on the lathe to get a flush and clean finish and then on the mill alongside an indexing head to drill the side holes all together. This would ensure that the holes are perfectly aligned and at exactly 120 degrees from each other. In the prototype presented on this paper, this was not the case and when assembling, the user must make sure to align the witness holes on the side to make sure both parts fit together with no issues and can be screwed easily.

Moreover, another suggestion would be to make the universal joints from scratch. Making them this could allow the user to machine, say on of the universal joints side and the connecting pin as a single part removing the need of set screws which have proven to be complicated to work with due to size of the device. In a similar way, the press fitted pins, risers and universal joint on the bottom plate could all become a single part making it stronger and easier to work with. When making these part and additional alignment feature could be added so that the actuators position is defined from the start. In the current assembly, this causes some issues as the user must align them and perfect alignment cannot be guaranteed as it is all done by "eye".

In terms of design, the base plate configuration has the largest room for improvement. To begin, the connection between the sawyer base plate and the platform base plate could be simplified and better constrained. Rather than using three screws with extruded knobs, which requires the aluminum knobs to bend inward to fully constrain the plates, a latch connection could be used with only one fastener. This would lessen the material needs of the two plates and better constrain the plates together.

Another improvement to the base plate configuration could be shelling more material out of the center of the platform base plate. There is only a need for material on this plate in a thin outer ring where the dowel pins, PCB screws, and sawyer plate connection lie. Otherwise, material in the center could be completely removed to save weight. Having a gap in the middle could also leave room for the PCB to be sunk into the base plate, rather than sitting on top of the plate. This could allow the dowel pins to be shorter, lessening their chance of bending and failure, and would reduce the total height of the device.

ACKNOWLEDGMENTS

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REFERENCES

Shigley's Mechanical Engineering Design Textbook.

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APPENDIX A

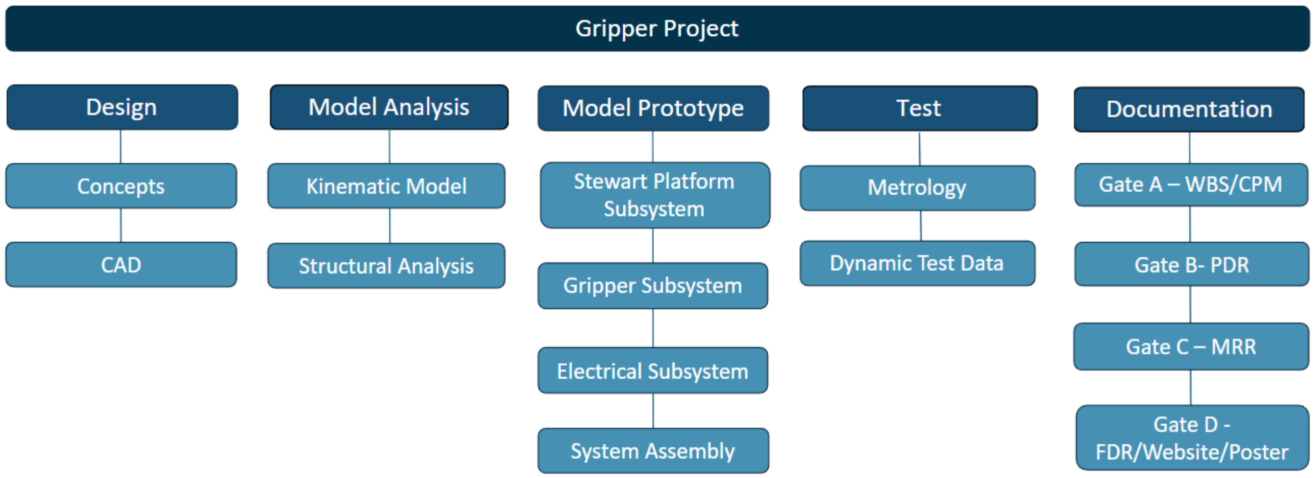

Figure 1: WBS including the fourteen deliverables of this project. The primary systems are in dark blue, and their corresponding subsystems (deliverables) are in light blue.

Table 1: The seven specifications of this project, with their values, units and methods of evaluation.

Specifications	# Value	Units	Description	Method of Evaluation (brief description)
1	3	cm	Minimum Translation in the x, y and z in the base frame	Measure starting vs end point (extremes)
2	30	deg	Minimum Rotation about x, y in the base frame	Keep stationary and only rotate (verify change in angle)
3	0.5	kg	Minimum payload able to be held securely by gripper	Having the device holds a 0.5kg object and moves through all 6 DOF without failure or device release.
4	10	cm	Maximum device size (cylinder envelope height, not including height of gripper)	Test with a space envelope in CAD and a physical (sturdy cardboard/wood) envelope on prototype.
5	8	cm	Maximum device size (cylinder envelope diameter)	Test with a space envelope in CAD and a physical (sturdy cardboard/wood) envelope on prototype.
6	2	kg	Maximum mass of gripper and wrist	Weigh gripper and wrist
7	15	deg	Minimum Rotation about z in the base frame	Keep stationary and only rotate (verify change in angle)

Table 2: Pugh matrix of the different Stewart Platform setup, focusing on the applications the mechanical system will experience.

Criteria	Type 3-3	Type 3-6	Type 6-3	Type 6-6
Workspace (Range of Motion)	0	0	0	Baseline
Stresses (previous slide)	+1	-1	-1	Baseline
Ease of Fabrication & Assembly	-1	-1	-1	Baseline
Cost	-1	-1	-1	Baseline
Total	**-1**	**-3**	**-3**	**0**

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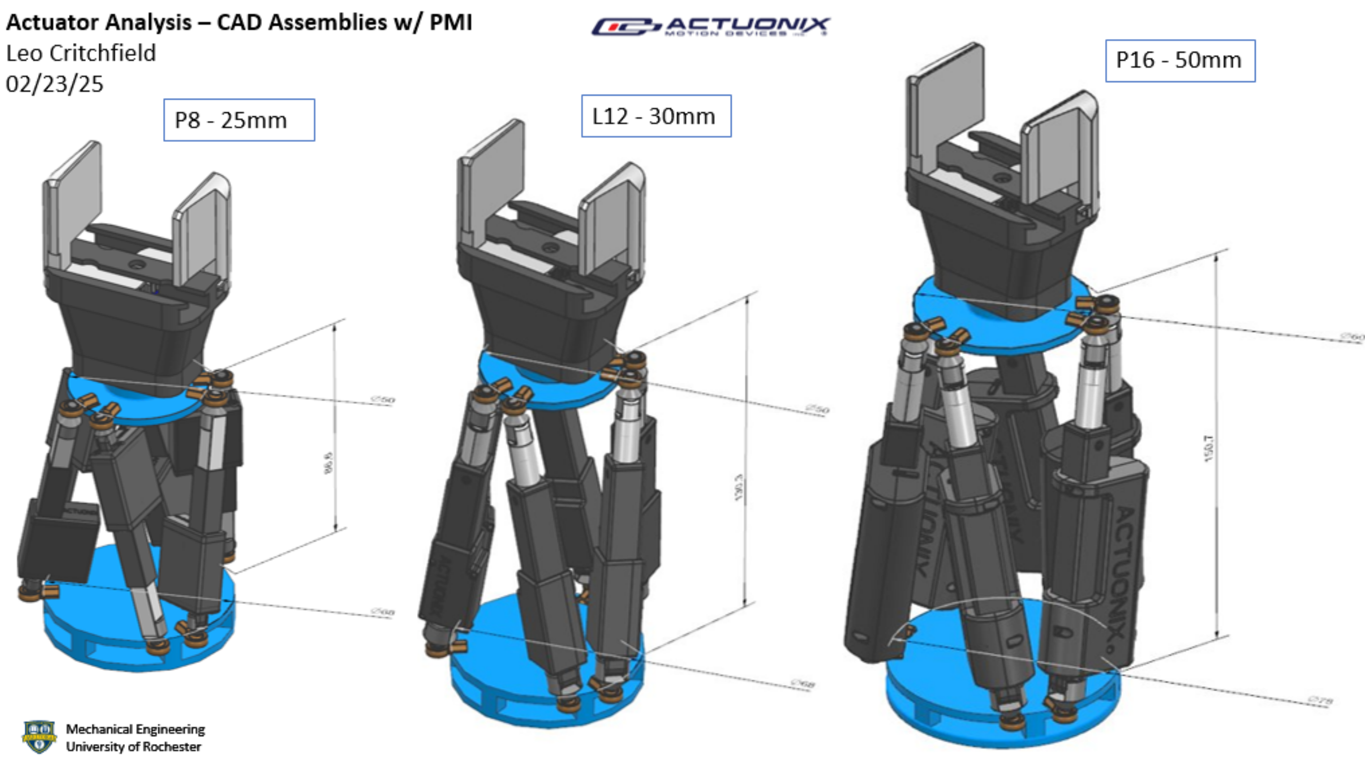

Figure 2: Actuator Assemblies used for Pugh matrix.

Table 3: Simulation of multiple actuators with their respective specifications with a focus on the requirements for this project.

	Height (base plate to motion plate with 50% actuator extension) *base CSYS*	**Diameter** (maximum including actuators)	**Max Translation** (net from base coordinate system)	**Max Rotation** (net from base coordinate system)	**Max Force** (lifted force in direction of actuation with highest gear ratio)	**Max Speed** (speed possible with lowest gear ratio and no load applied)	**Stall Current** (max current at 12V operation)	**Electronic Control** (type of microcontroller interface, position output is a plus)	**Mass** (per actuator)	**Interference Likelihood** (chance of actuator bodies colliding with movement) *to be tested*
P8 25mm Actuator	100mm	80mm	24mm (Z), 66mm (X,Y)	90deg (Z), 60deg (X,Y)	155N	30mm/s	450mA	External Position Controller	26g	Medium
L12 30mm Actuator	130mm	80mm	29mm (Z), 86mm (X,Y)	90deg (Z), 60deg (X,Y)	80N	25mm/s	246mA	Internal Position Controller w/ analog position output	34g	Low
P16 50mm Actuator	150mm	90mm	48mm (Z), 120mm (X,Y)	50deg (Z), 90deg (X,Y)	300N	46mm/s	1000mA	External Position Controller	95g	High

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Table 4: Pugh matrix of three linear actuators of choice, based on the mechanism of a Stewart Platform.

Criteria	P8-R (25mm)	L12-I (30mm)	P16-R (50mm)
Height Parameters	Baseline	-1	-1
Diameter Parameters	Baseline	0	-1
Translation Specifications	Baseline	+1	+1
Rotation Specifications	Baseline	0	0
Max. Force	Baseline	-1	+1
Max. Speed	Baseline	-1	+1
Stall Current	Baseline	+1	-1
Electronic Control	Baseline	+1	0
Mass	Baseline	-1	-1
Actuator Interference Possibility	Baseline	+1	-1
Total	**0**	**+1**	**-2**

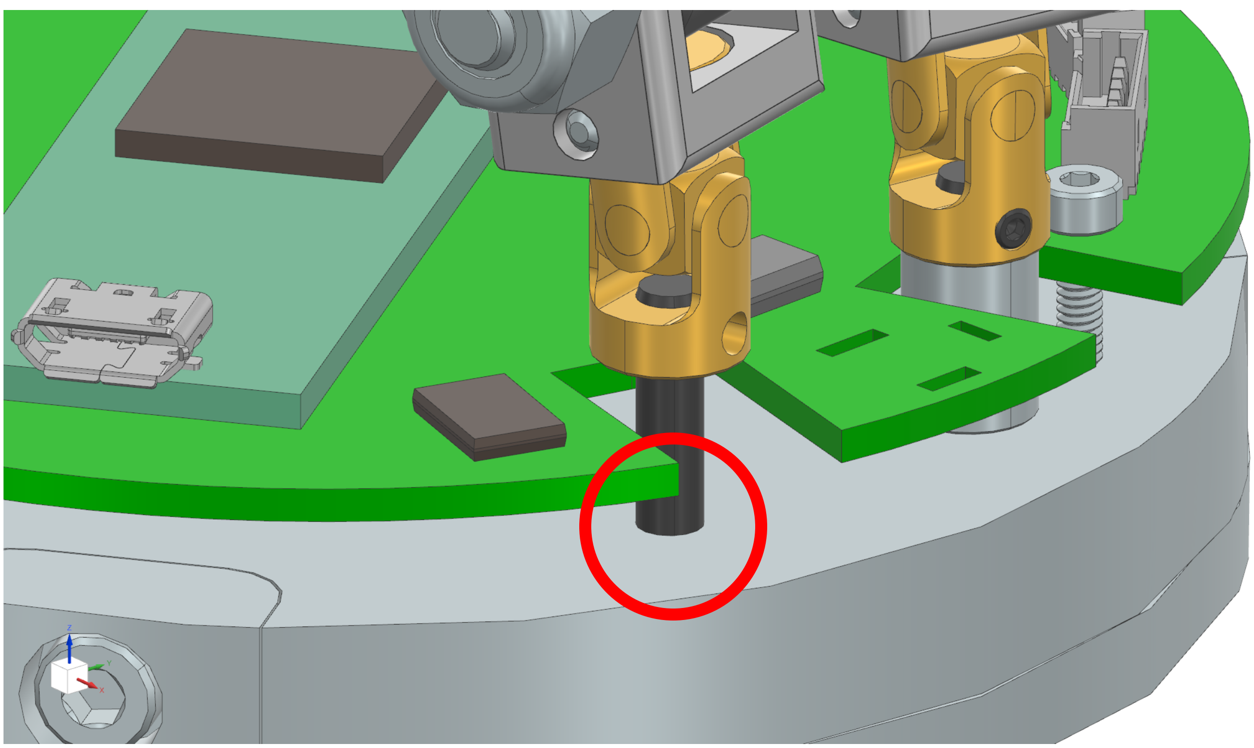

Figure 3: Connection between the diameter of the hole of the base plate and the outer diameter of pin that connects this plate to the universal joints. Both components have an interference fit (ISO System: H7/p6), where the base plate holes have a tolerance of 3mm (+0.002/0.000).

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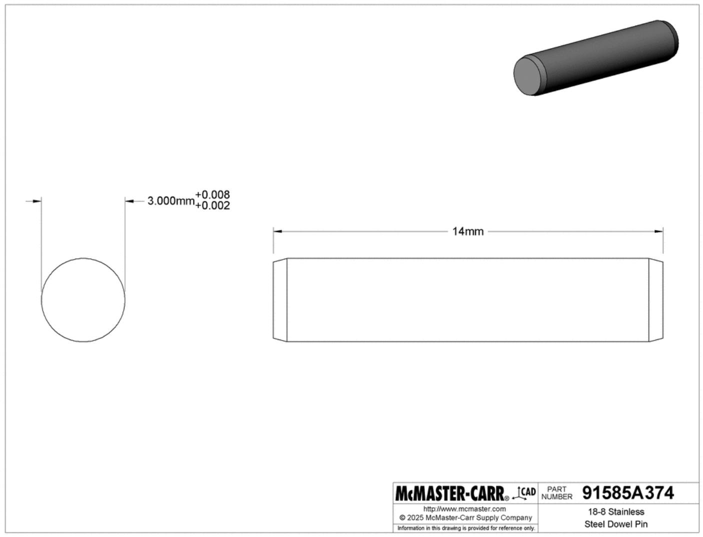

Figure 4: Pin used in the mechanical system to connect the base plate to the universal joint. This component has a tolerance of 3mm (+0.008/+0.002) for an interference fit (X/X)

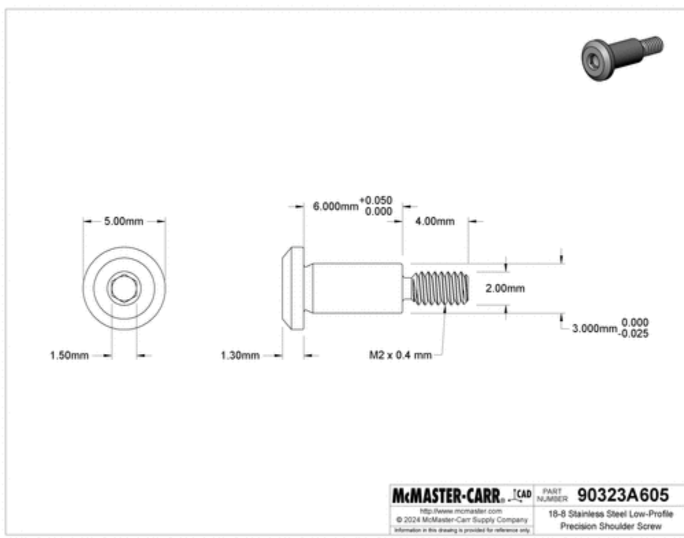

Figure 5: Shoulder Screw used in the top plate, which acts as a shaft in the tolerance analysis. This was used with a sliding fit (H7/g6) with the dimension 3.000mm (0.000/-0.025) between this shoulder screw and an oil-embedded bushing.

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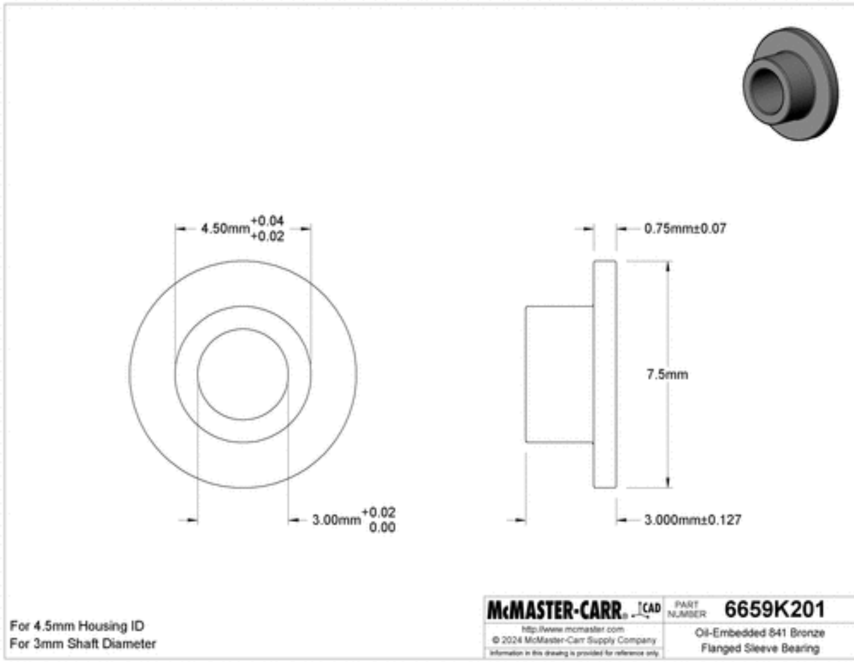

Figure 6: Oil-embedded bushing used in the top plate, which acts as a hole in the tolerance analysis. This was used with a sliding fit (H7/g6) with the dimension 3.000mm (+0.02/0.00) between the shoulder screw and the oil-embedded bushing.

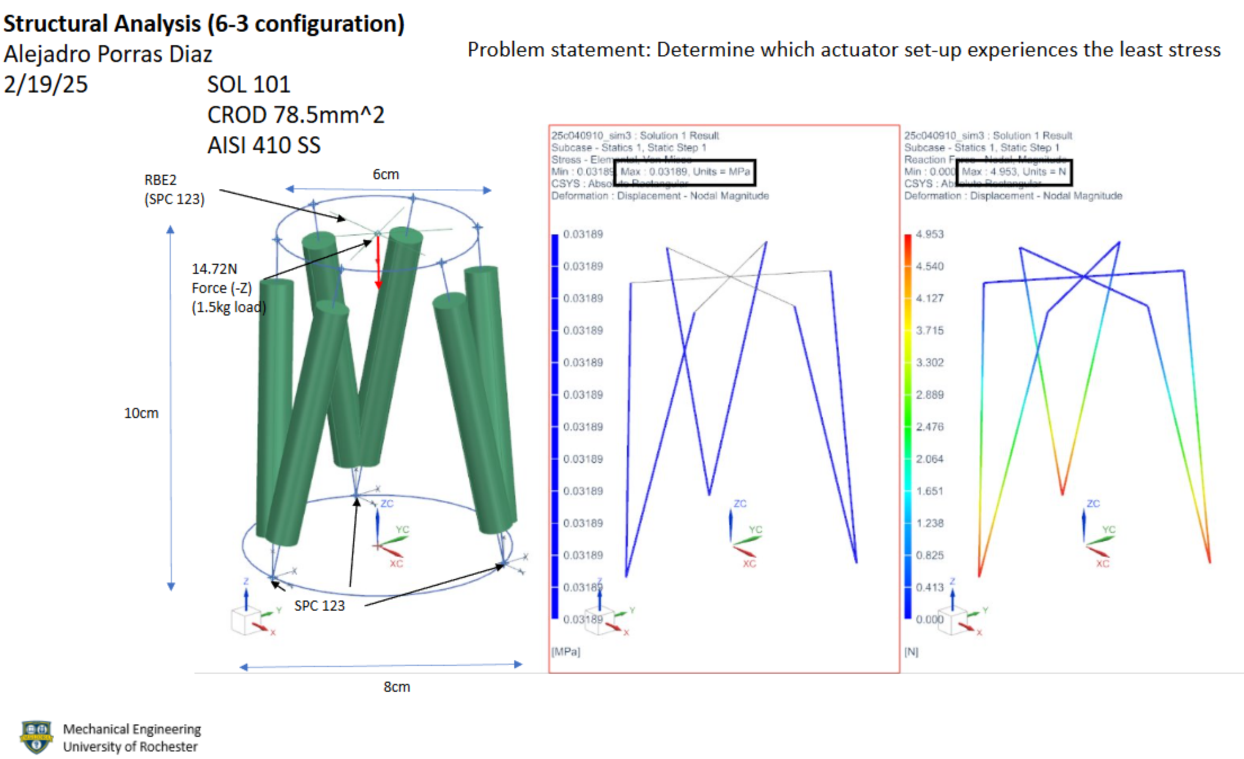

Figure 7. Shows a structural analysis on NX of type 6-3 hexapod set up.

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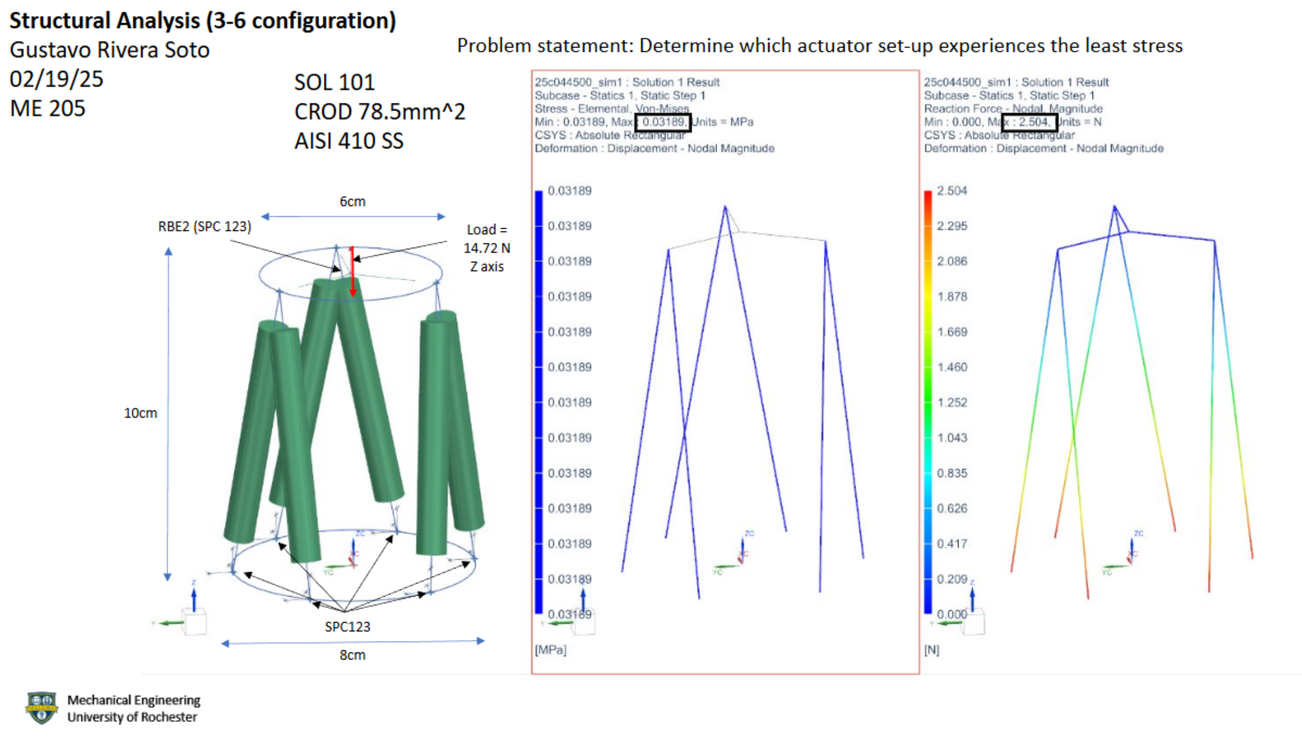

Figure 8. Shows a structural analysis on NX of type 3-6 hexapod set up.

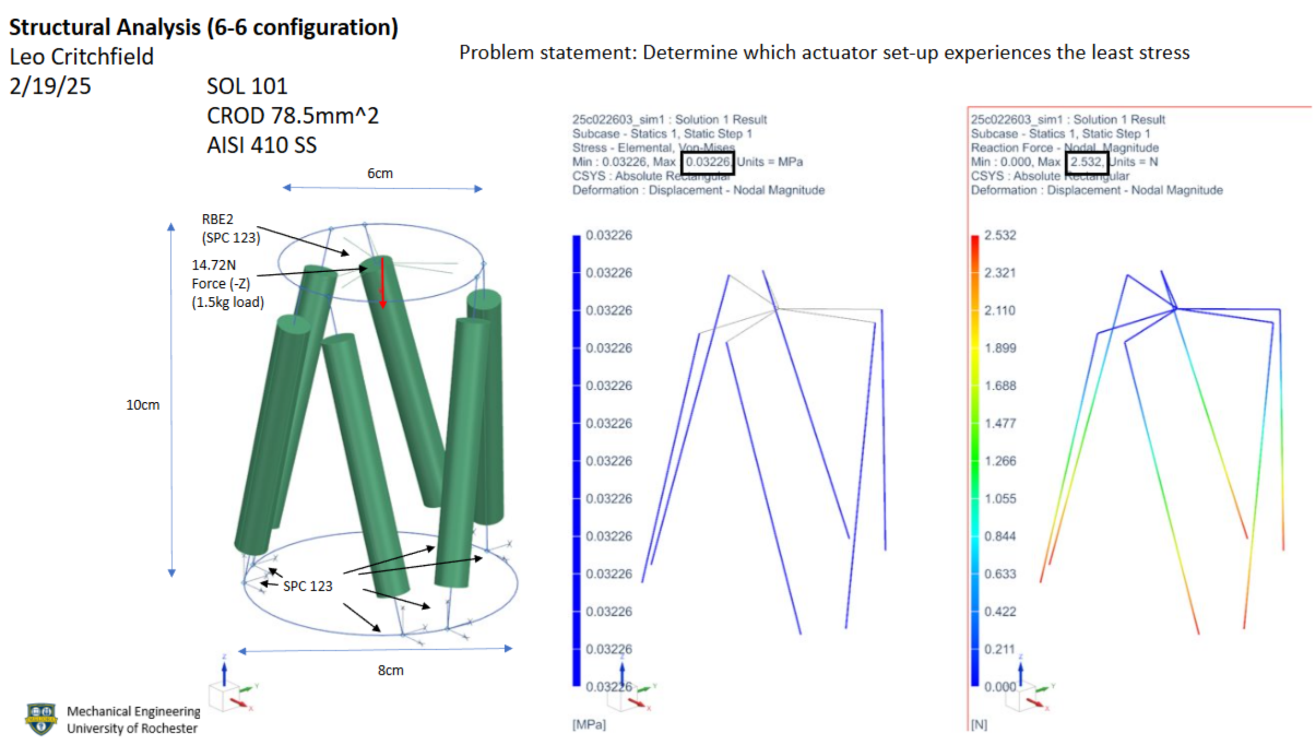

Figure 9. Shows a structural analysis on NX of type 6-6 hexapod set up.

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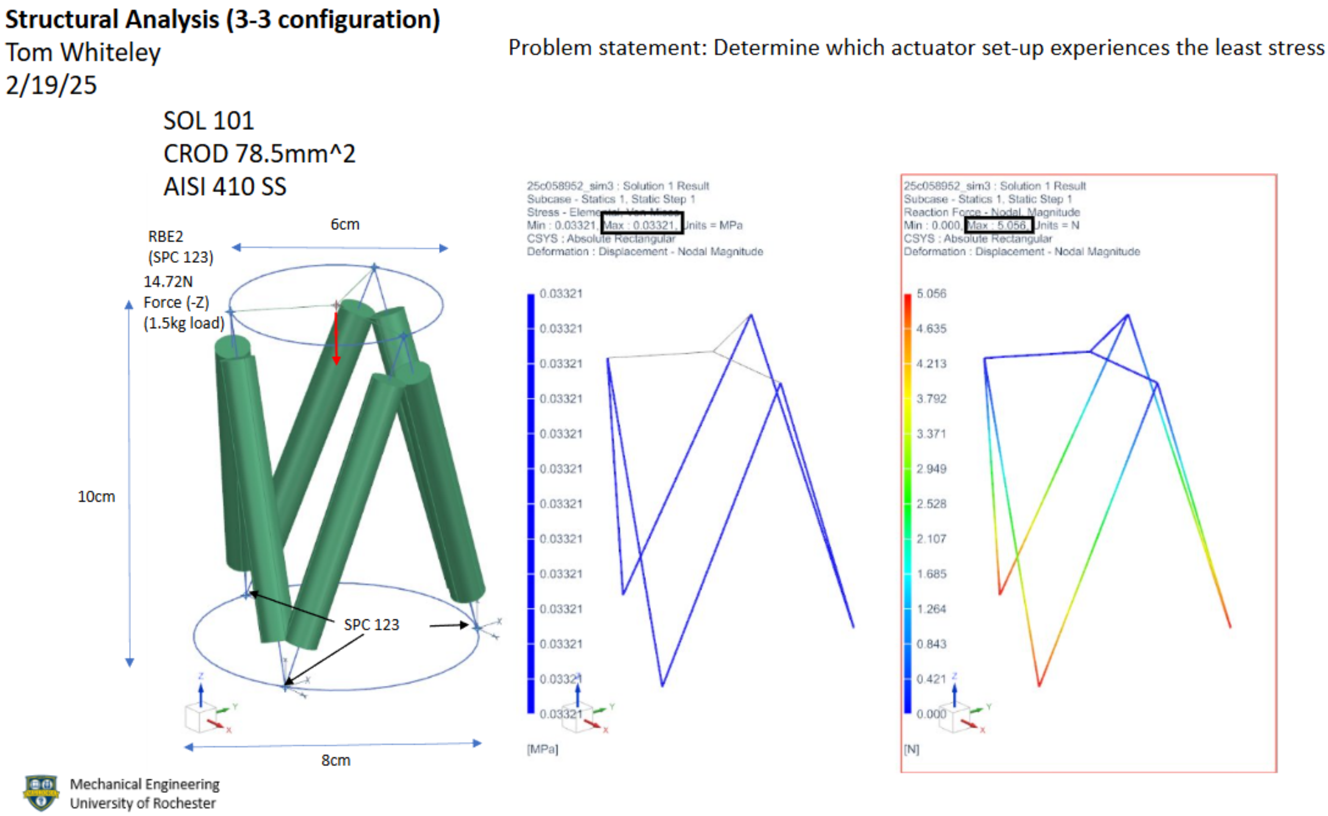
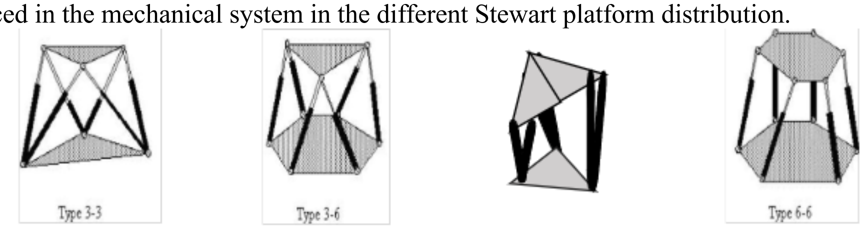


Figure 10. Shows a structural analysis on NX of type 6-3 hexapod set up.

Table 5: Pugh matrix of stresses experienced in the mechanical system in the different Stewart platform distribution.



Criteria	Type 3-3	Type 3-6	Type 6-3	Type 6-6
Max Stress (Force Applied -X)	0.166 MPa	0.276 MPa	0.276 MPa	0.251 MPa
Percent Difference from Baseline	-33.9%	+9.96%	+9.96%	Baseline
Max Stress (Force Applied -Y)	0.1917 MPa	0.319 MPa	0.319 MPa	0.247 MPa
Percent Difference from Baseline	-22.4%	+29.1%	+29.1%	Baseline
Max Stress (Force Applied -Z)	0.03321 MPa	0.0306 MPa	0.03189 MPa	0.03226 MPa
Percent Difference from Baseline	+2.86%	-4.99%	-1.11%	Baseline
Total:	-53.44%	+34.07%	+37.95%	0

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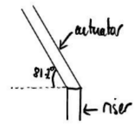
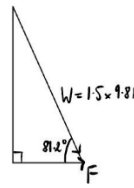
Analysis of adding Risers (Cantilever Beam problem):

$$\cos\theta = \frac{12.5}{82} \Rightarrow \theta = 81.2^\circ$$





$$\cos 81.2 = \frac{F}{1.5\times 9.81} \Rightarrow F = 2.24\,N$$

$$\sigma = \frac{My}{I} = \frac{(2.24)(8\times10^{-3})(3\times10^{-3})}{\frac{\pi (6\times10^{-3})^4}{64}} = 845\text{ kPa}$$

845 kPa < 30MPa ∴ passes under bending stress

↑ yield strength of Al.

$$\tau_{max} = \frac{4V}{3A} = \frac{4}{3}\frac{(2.24)}{\pi(3\times10^{-3})^2} = 106\text{ kPa}$$

106 kPa < 207 MPa ∴ passes under shear stress

↑ Shear strength of Al

Figure 11 shows a cantilever beam analysis produced to analyze the bending and shear stress acting on the dowel pins which the universal joints sit on.

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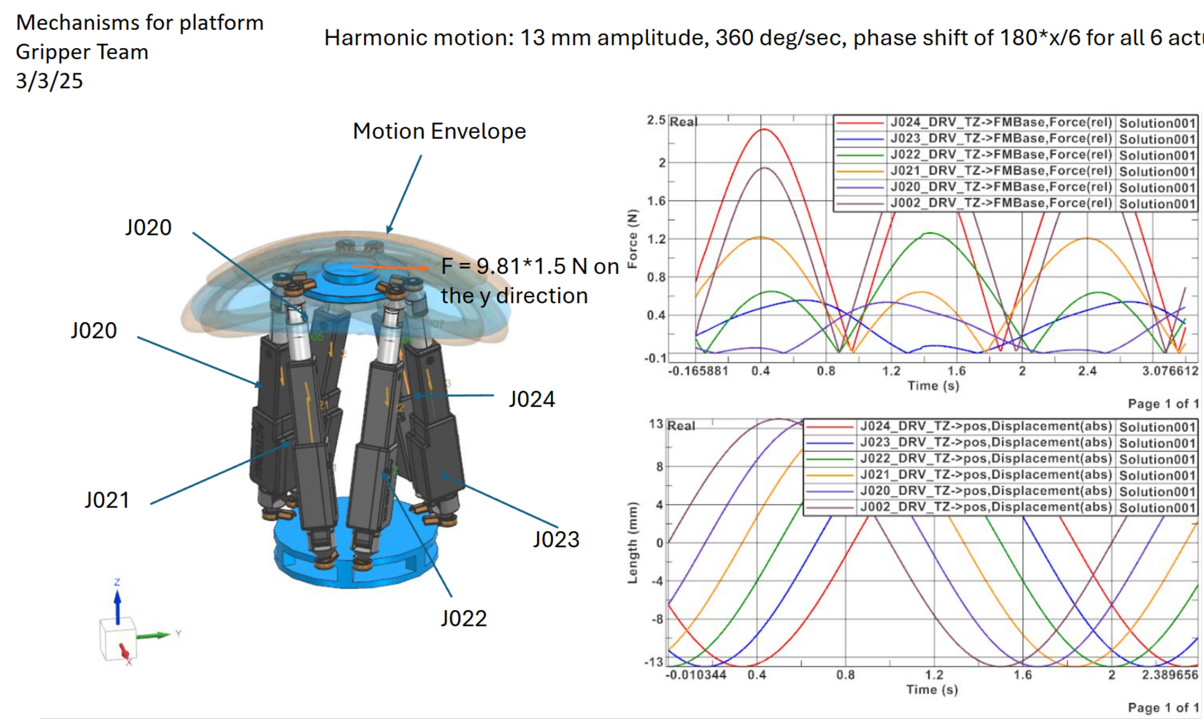

Figure 12: Mechanical simulation of the Stewart Strut and the reactions on the base and actuators motion. Maximum reaction force around ~2.5N for the base (universal joints).

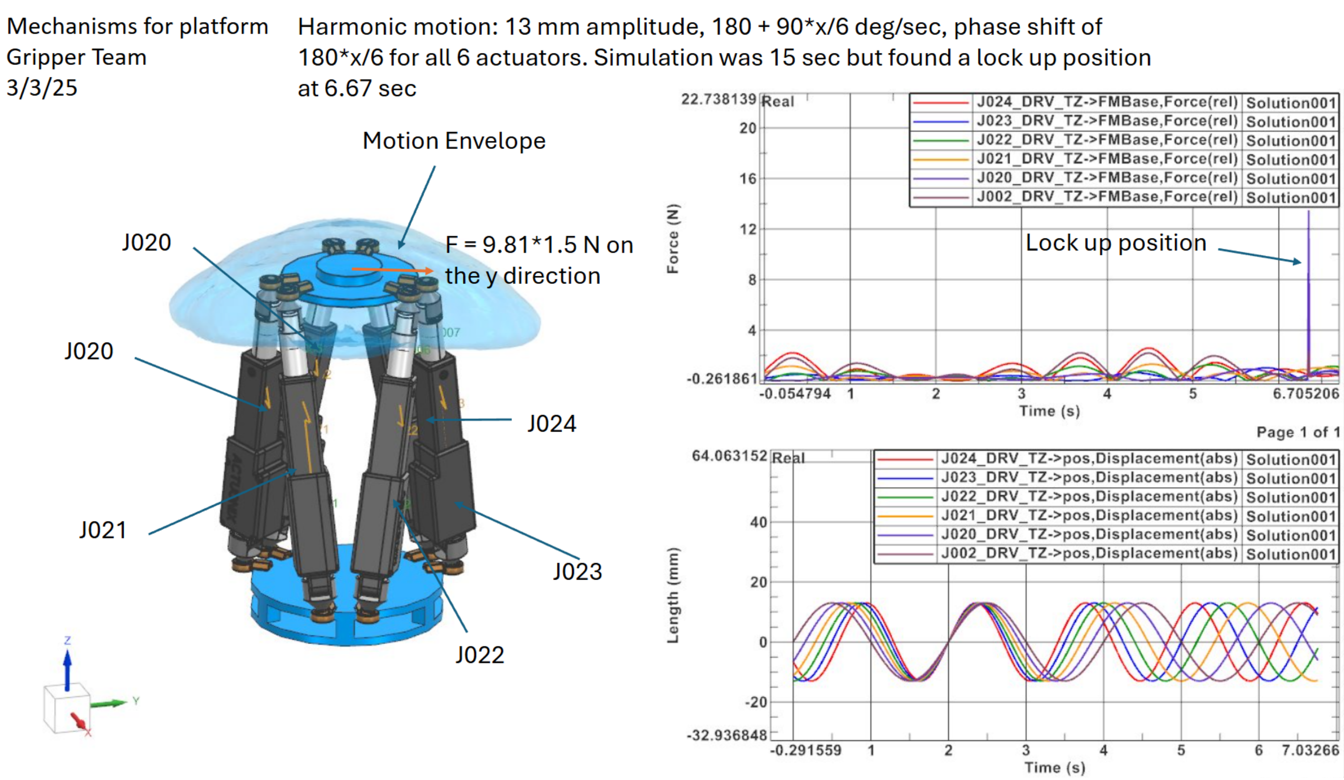

Figure 13: Mechanical simulation of the Stewart Strut and reactions on the base and actuators motion. Maximum reaction force spikes to ~14 N (lockup position).

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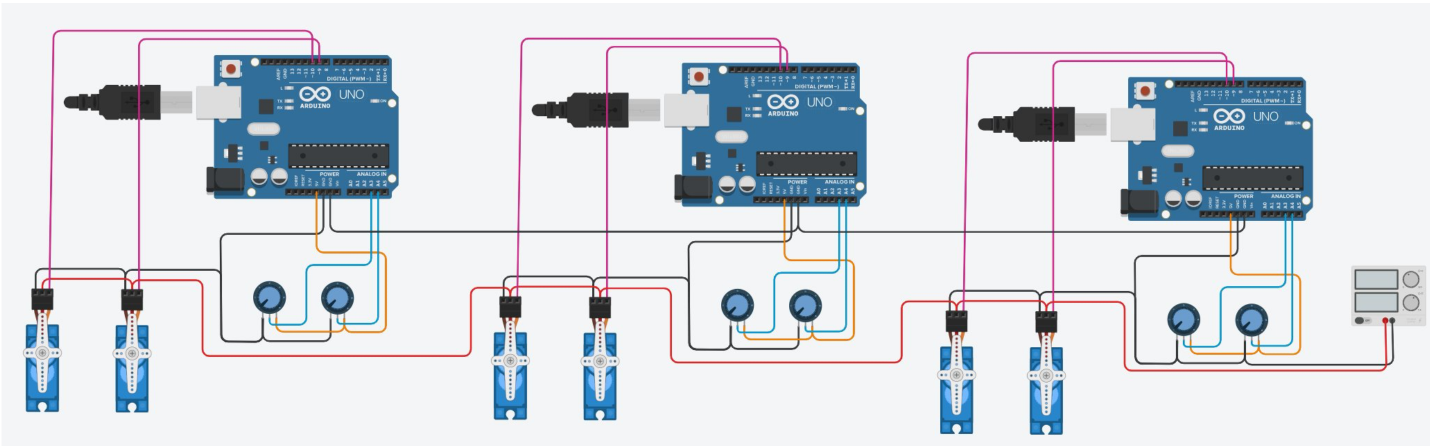

Figure 14. Circuit diagram to drive all six actuators, controlled via an individually paired potentiometer. Each Arduino is responsible for reading signals from two potentiometers and driving two actuators.

Table 6: Test data obtained against specifications values

Specification	Required	Tested	Pass/Fail
Minimum translation in the x, y, and z coordinates in the base frame.	3 cm	Z: 2.93 X: 4.3 Y: 4.1	PASS
Minimum rotation about x and y coordinate axis in the base frame.	30°	X: 33.1° Y: 38°	PASS
Minimum rotation about the z coordinate axis in the base frame.	15°	60.8°	PASS
Maximum device height.	15 cm	14.94 cm	PASS
Maximum device diameter.	8 cm	8 cm	PASS
Minimum payload to be held securely by the gripper.	0.5 kg	0.8 kg	PASS
Maximum mass of the whole assembly	2 kg	0.674 kg	PASS

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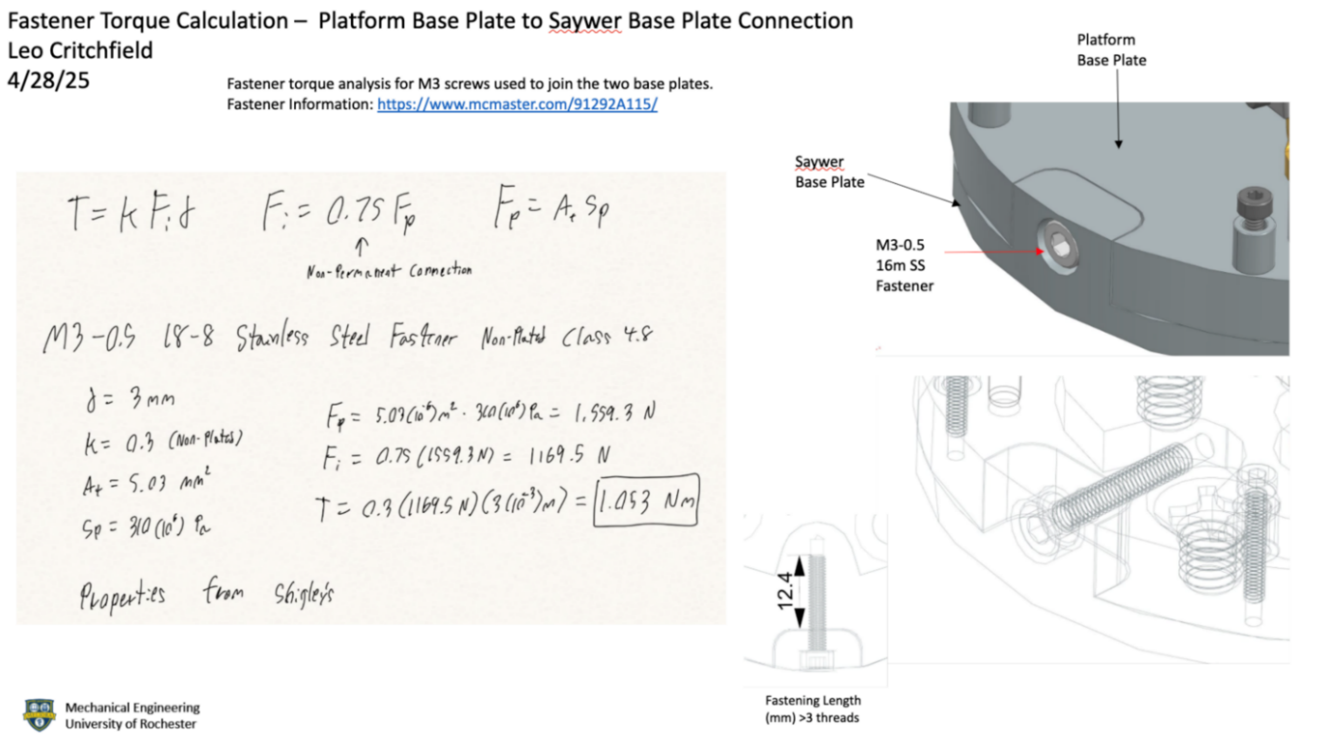

Figure 15. Fastener torque calculation for the 3 screws which join the two base plates. The required torque is 1.053 N*m.

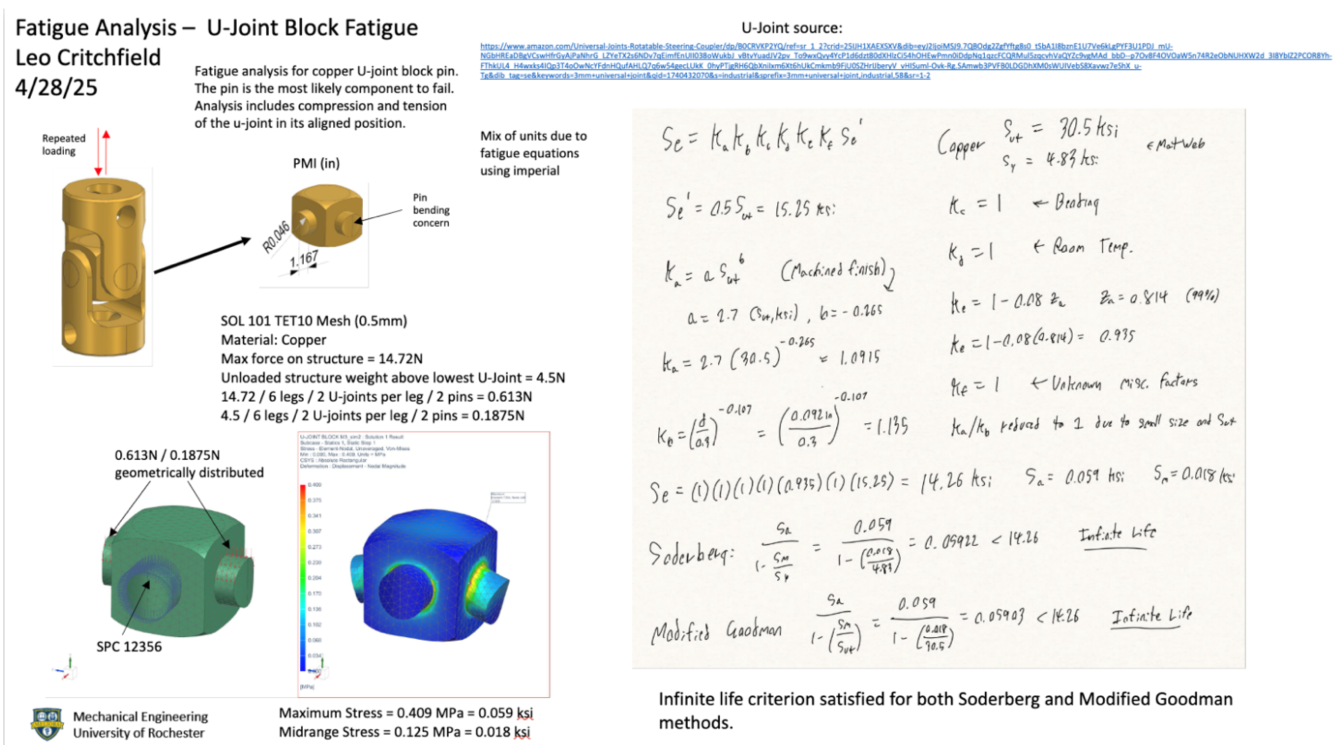

Figure 16. Fatigue analysis for the U-Joint's connecting block pins. The infinite life criterion is satisfied for these pins based on the applied loads to the device.

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APPENDIX B – CAD

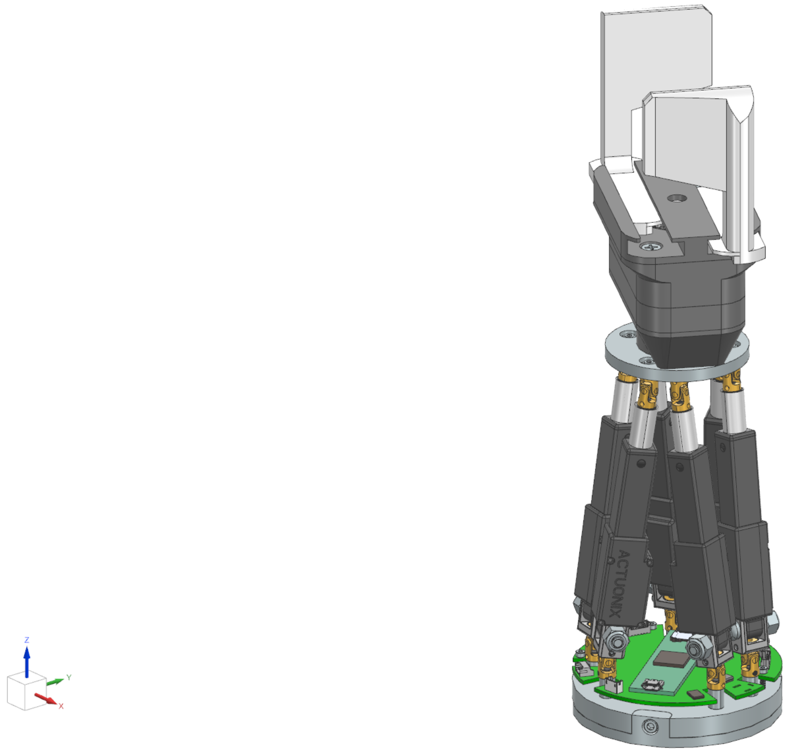

Figure 1. The final CAD version of the mechanical wrist assembly with both the gripper and the Stewart strut subassemblies.

Figure 2. The mechanical wrist assembly interfacing with the Rethink Robotics Sawyer Platform, meeting one of the deliverables.

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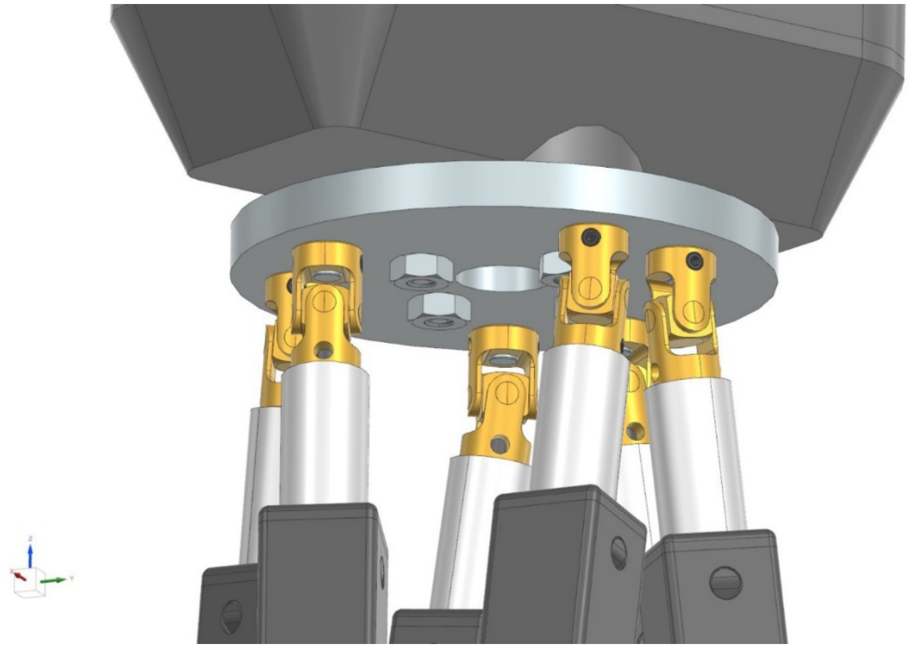

Figure 3. Close up image of the top portion of the assembly. As observed in the image, the actuators and the top plate are connected through universal joints. These are capable of spinning about the top plate holes axis due to the application of the sliding fit between the bushing and the screws holding the universal joints.

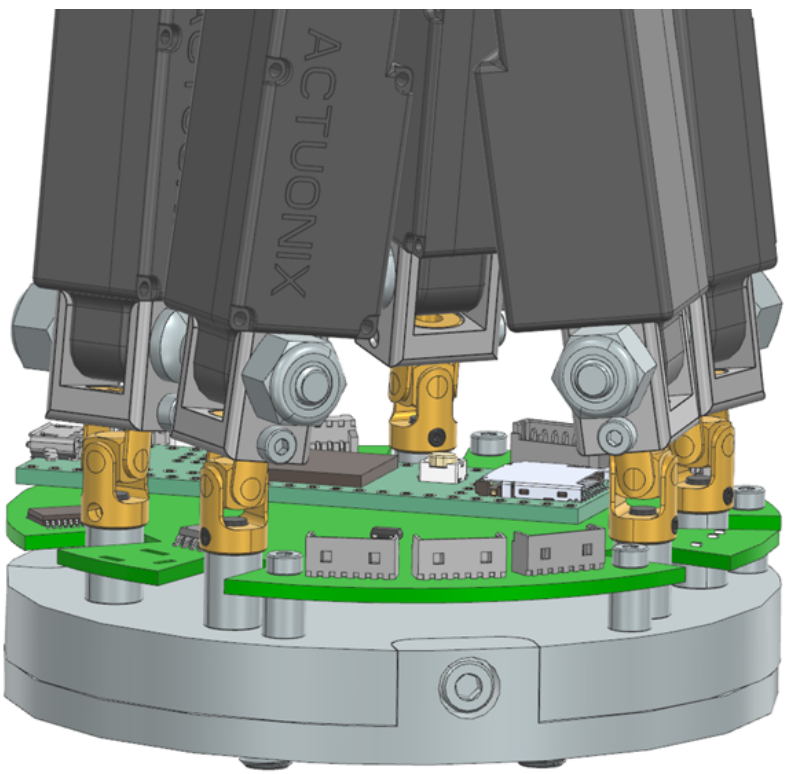

Figure 4. Close up image of the bottom portion of the assembly. Spacers were used to provide enough space for the PCB board, inside the space envelope, without the possibility of interfering with the universal joints or the actuators. Additionally, an illustration of the usage of the connecting block to create one body motion between the universal joints and the actuators.

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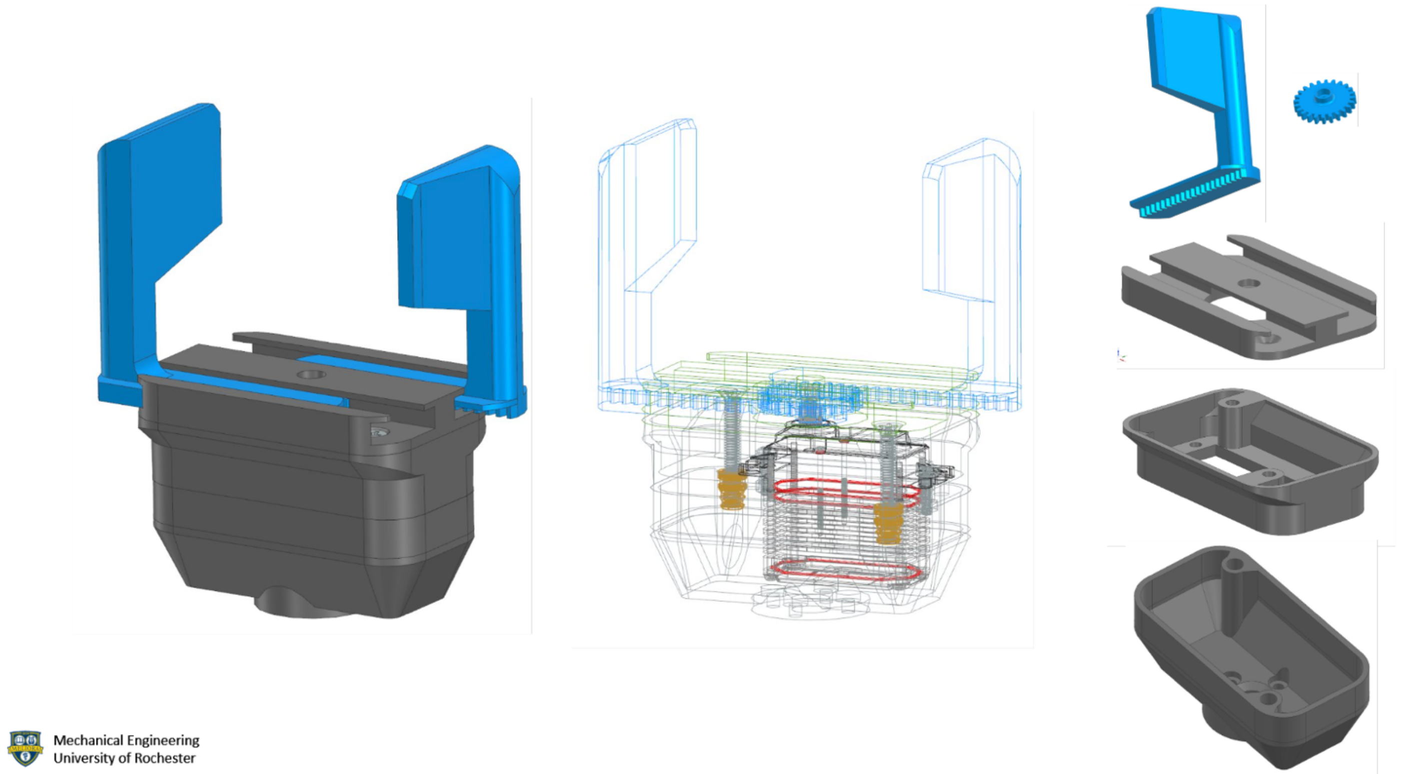

Figure 5. Gripper final design. A modular design was chosen to allow for 3D printing of the body. Both arms are operated by one servo for simplicity and compactness.

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APPENDIX C – DRAWING PACKAGE

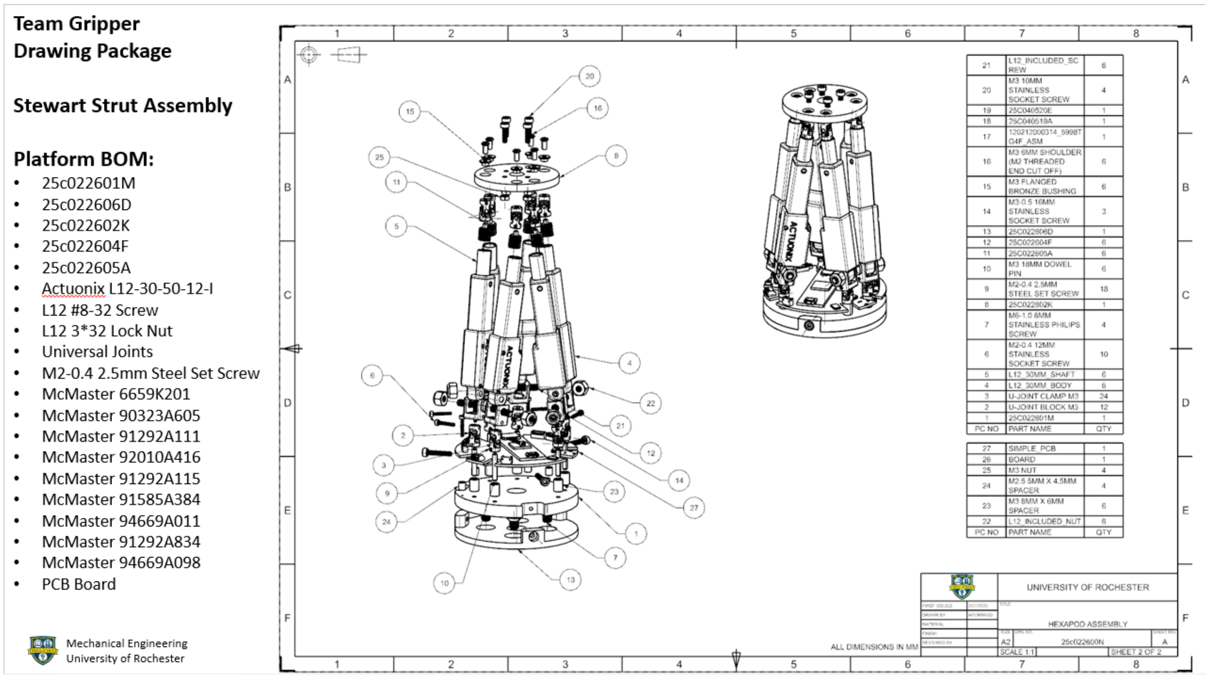

Figure 1: Drawing Package of the Stewart Strut subassembly with a bill of materials of all the components (including parts that were bought on the market)

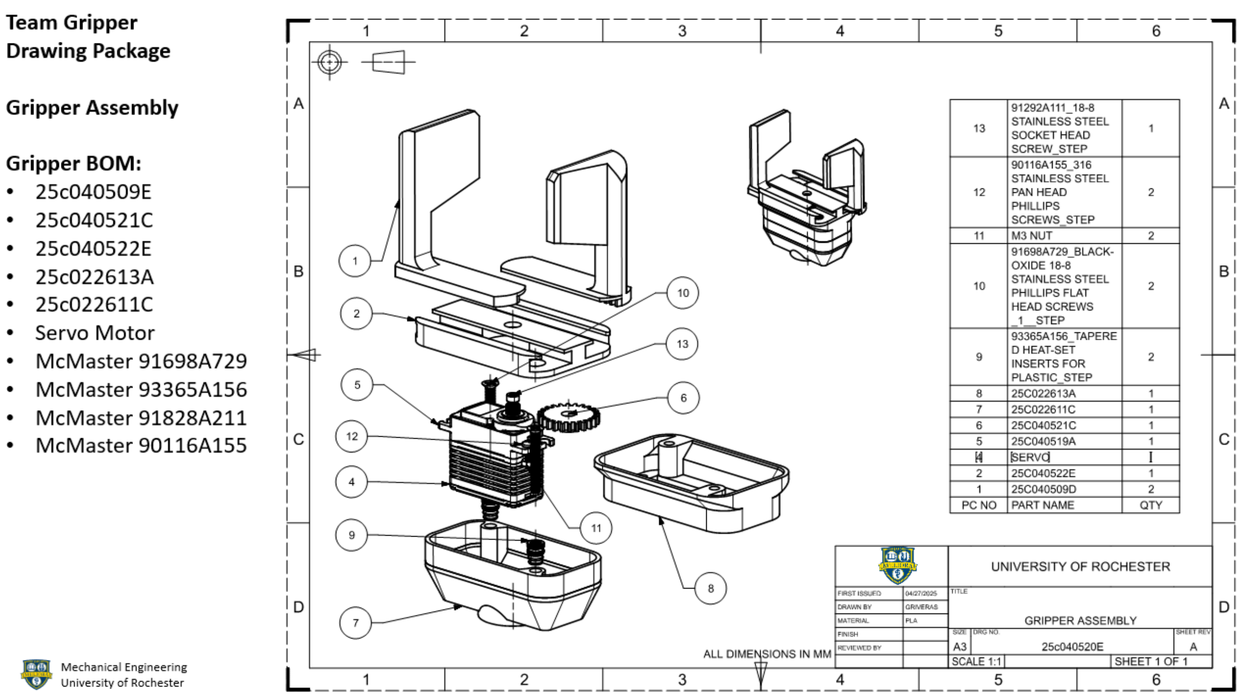

Figure 2: Drawing package of the gripper subassembly with a list of materials of all the components present in this assembly.

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APPENDIX D – TESTING

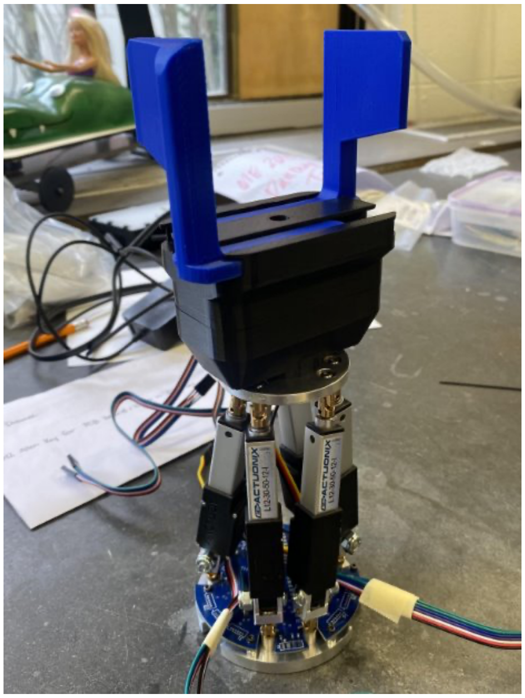

Figure 1. Image of the mechanical wrist assembled. Note: the PCB board used in the image is a prototype used for visual representation, rather than the one corresponding to the system.

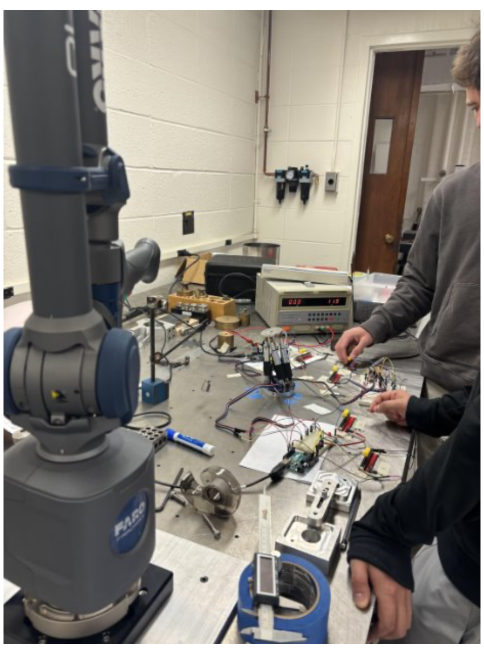

Figure 2. Image of the setup for testing. Testing was performed with the Quantum X FaroArm® located in Hopeman 121 at the University of Rochester

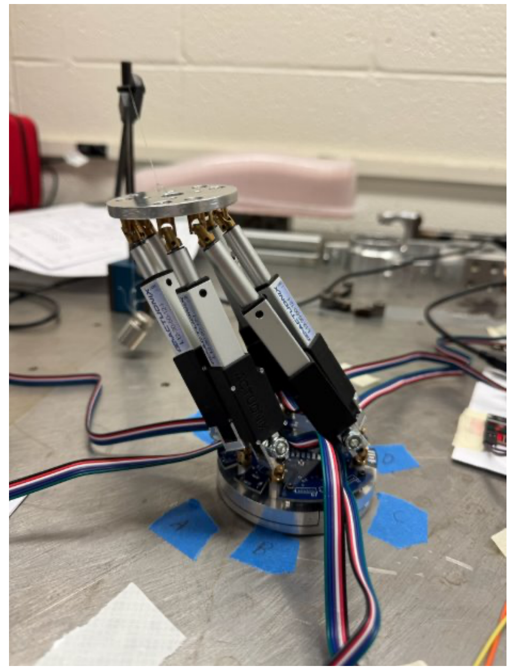

Figure 3. Image of the mechanical system translating. From the zero position, the system translated approximately 4 centimeters, meeting the values established in the specifications.

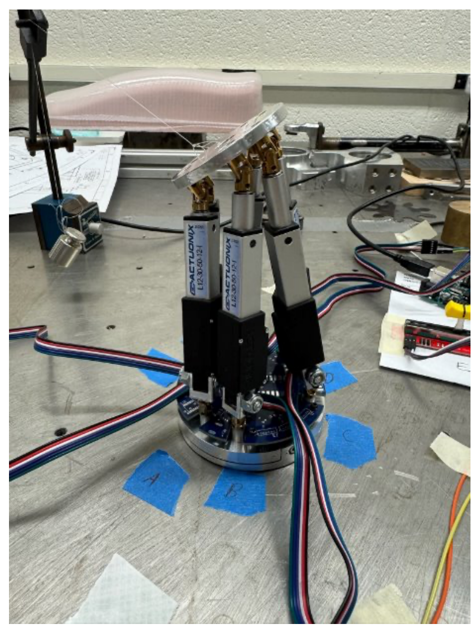

Figure 4: Image of the mechanical system tilting. From the zero position, the system tilted in the x and y approximately 33 and 38 degrees, respectively, which meets the values established in the specifications.

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