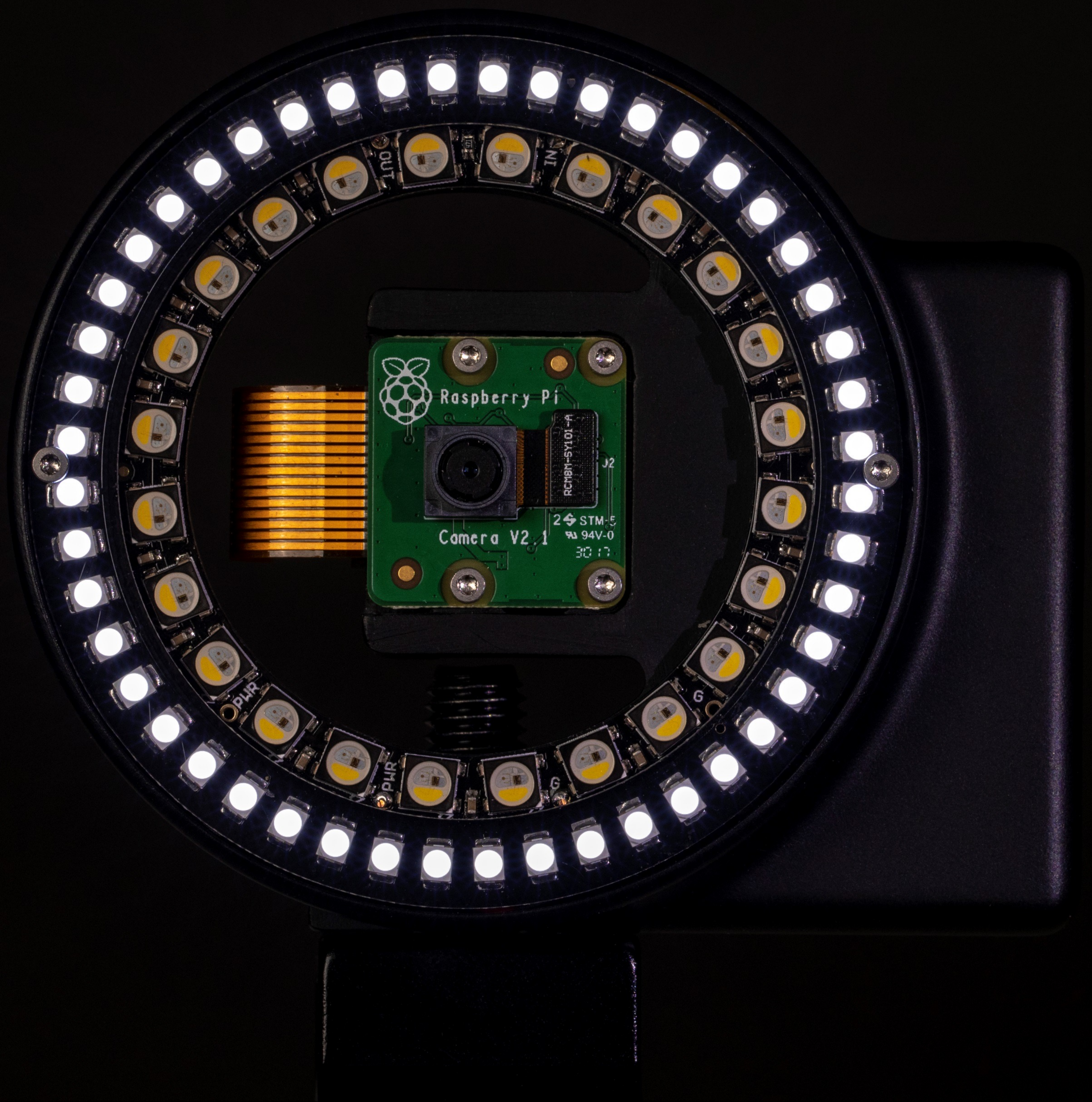
Aaron Jaeger

MIT Media Lab, MAS 2021
  Graduate Research Assistant,
  Biomechatronics

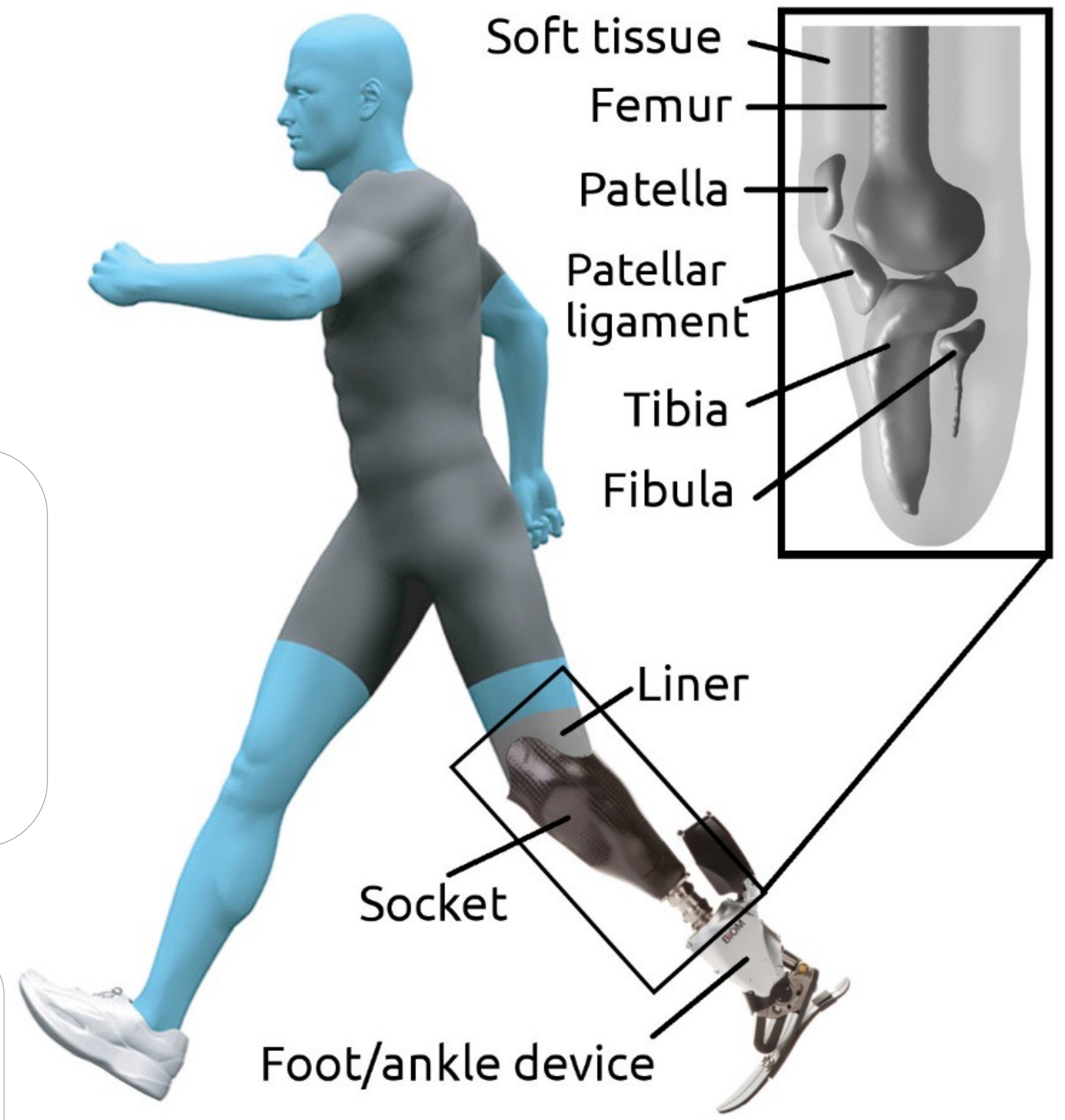
Robotics Engineering, WPI 2017



Biomechatronics Group, MIT Media Lab

Graduate Research Assistant, Master's Student	2019-2021
Senior Research Support Associate (SRSA)	2017-2019

> "The Biomechatronics group seeks to advance technologies that promise to accelerate the merging of body and machine, including device architectures that resemble the body's own musculoskeletal design, actuator technologies that behave like muscle, and control methodologies that exploit principles of biological movement."



Socket Team

Challenge: Prosthetic sockets are currently manufactured using manual labor and are bespoke to the wearer. This manual process is expensive and often inaccurate, leading to sockets that do not always fit properly or might be poorly constructed.

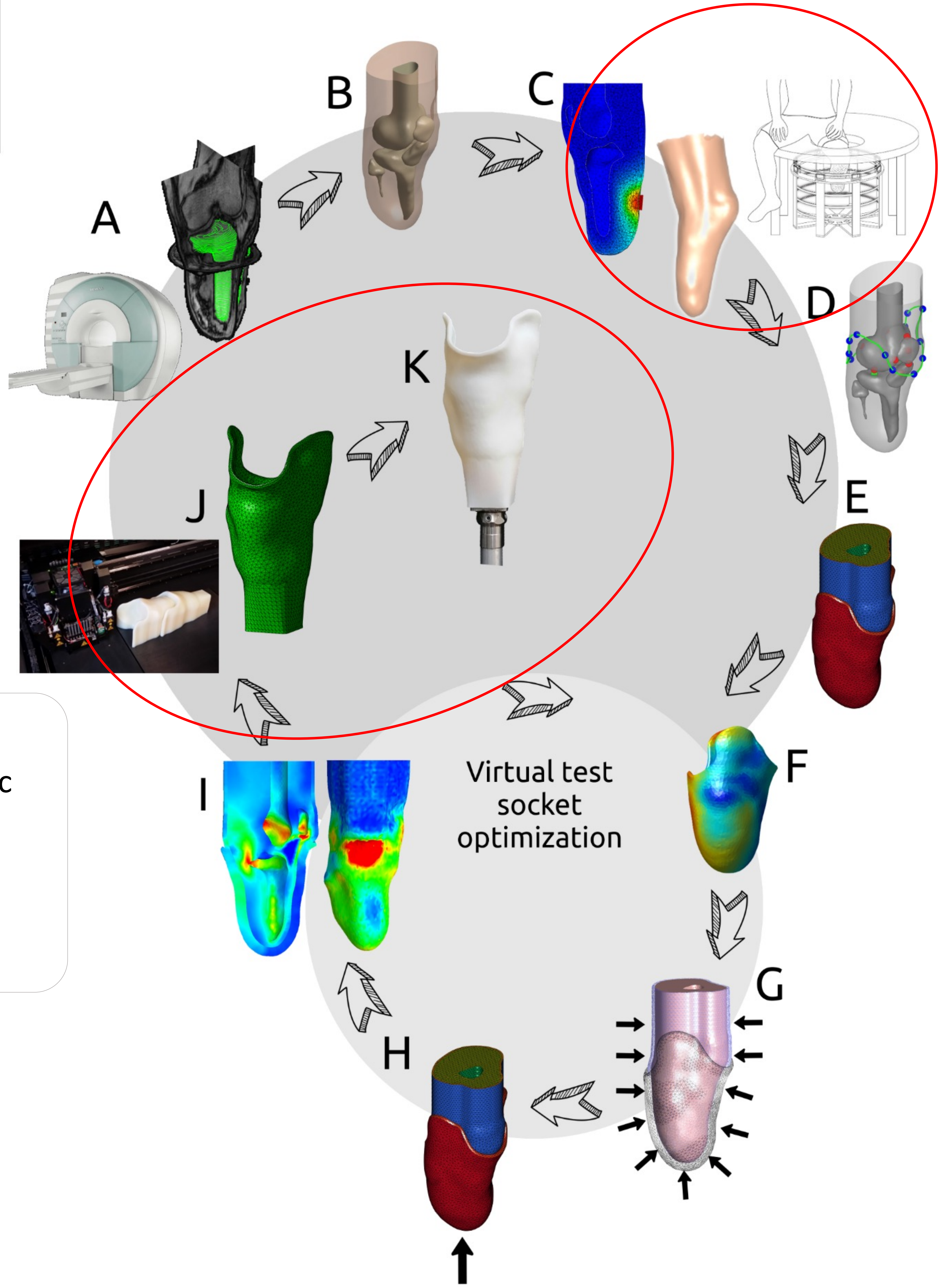
Goal: Develop a data-driven, computational design framework to design affordable, subject specific prosthetic sockets and replace the traditional manual process.

My Contributions

As Graduate Student: Prototyped a Desktop Automated Fiber Placement machine to manufacture carbon composite prosthetic sockets.

As SRSA: Designed and implemented a patient Scanner and Indenter to measure the time-varying 3D shape and mechanical properties of a residual limb.

Data-Driven Computational Socket Design Framework



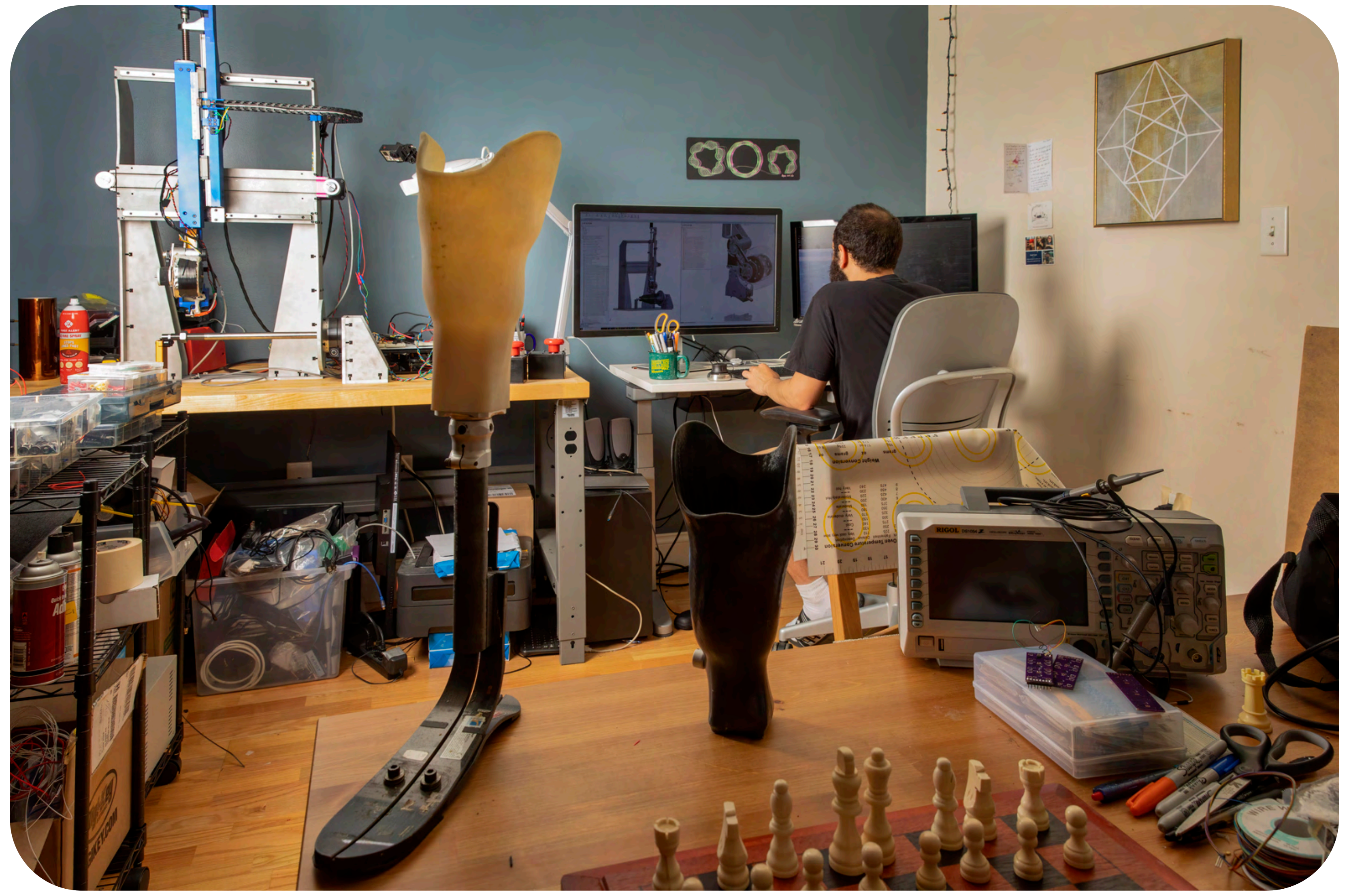
biomechatronics

Master’s Thesis - 2019-2021: Prosthetic Socket Fabrication

Project:
Prototyped a Desktop Automated Fiber Placement (AFP) machine to manufacture carbon composite prosthetic sockets.

Project Impact:
Desktop scale AFP machine for non-planar surfaces. This work aims to replace the current manual socket fabrication process that is expensive and often inaccurate, leading to sockets that do not always fit properly or might be poorly constructed.

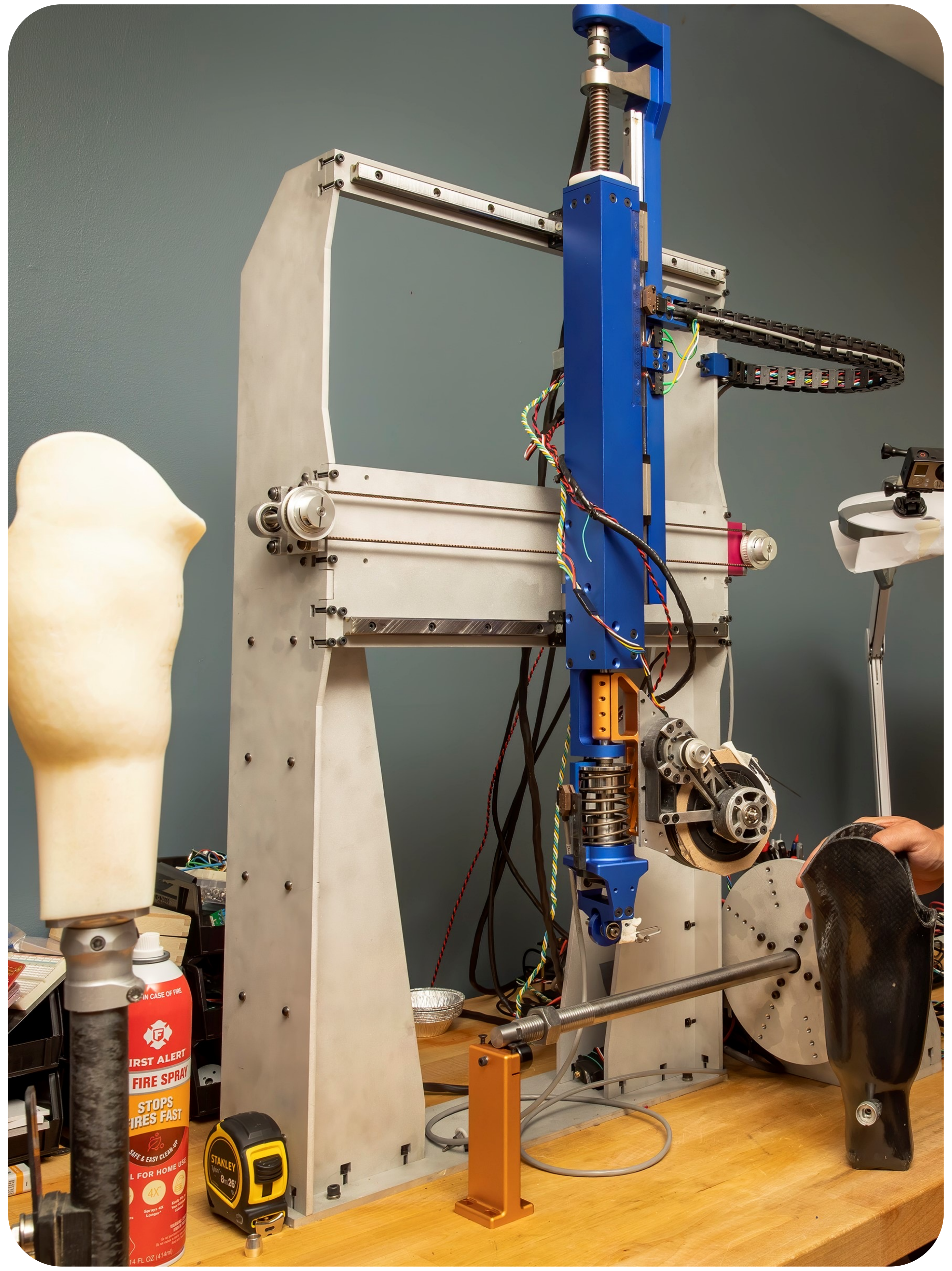
Project Type:
Thesis project. Independently to identified a problem, proposed a solution, then defined, analyzed, designed, built, programmed, tested, and evaluated the system.



Remote Media Lab Setup

Setup satellite Media Lab at home for use during the 2020-2021 Covid Pandemic

The Desktop AFP Prototype



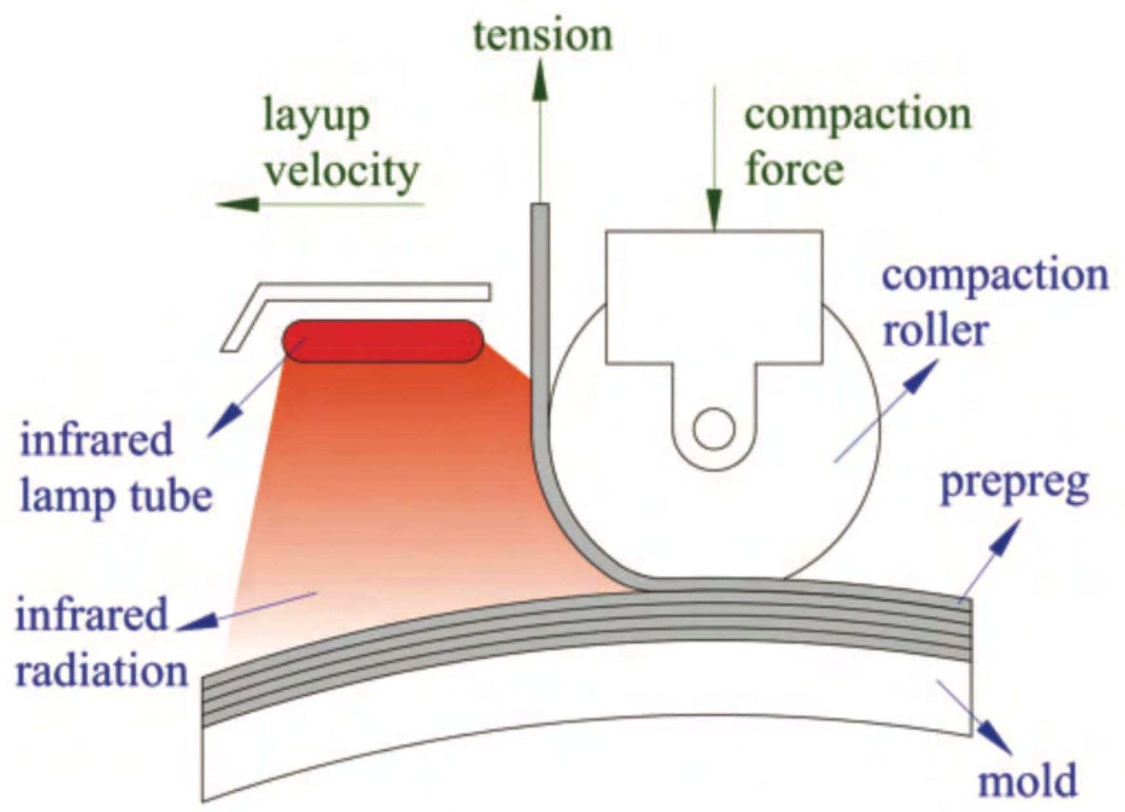
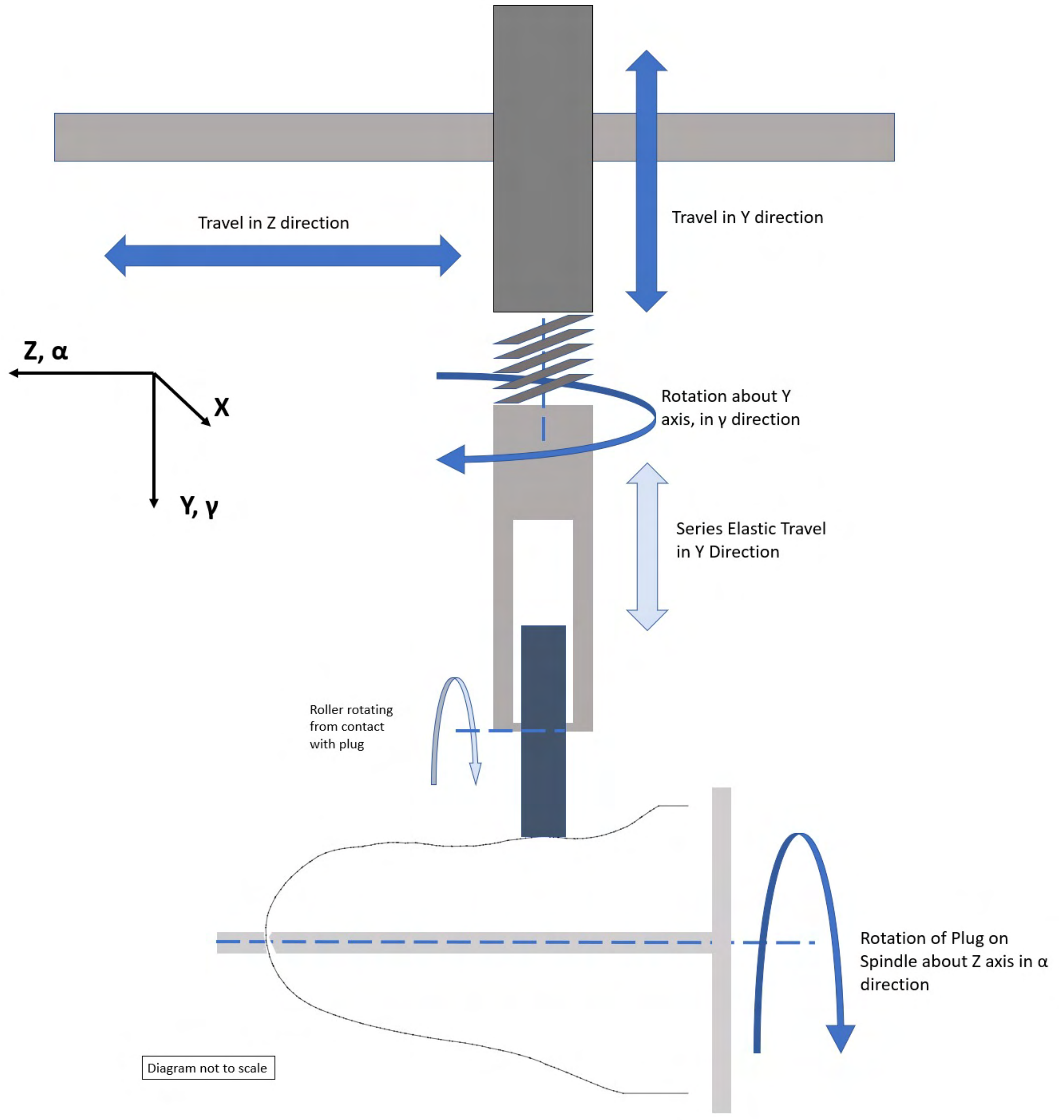


Figure 1. The automated fiber placement (AFP) process.

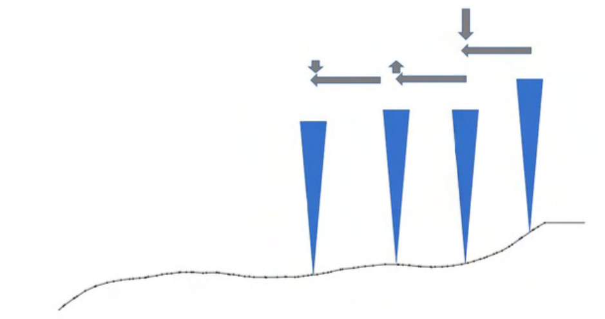
Jiang, J., He, Y., & Ke, Y. (2019). Pressure distribution for automated fiber placement and design optimization of compaction rollers. Journal of Reinforced Plastics and Composites, 38(18), 860–870. https://doi.org/10.1177/0731684419850896

Automated fiber placement (AFP) is a process commonly used in the aerospace industry to make large, complex composite parts where a robotic gantry lays down individual pre-impregnated strips of fiber tow. This thesis prototyped a proof-of-concept desktop AFP machine with four degrees of freedom designed for building prosthetic sockets for $10,000 at a scale feasible for small clinics, university research labs, and residential settings. The AFP prototype demonstrated the basic ability to automatically place and laminate strips of fiber. During testing the prototype demonstrated a constant compaction force at 75N with standard deviation of 1.2N over varying surface and of produced the 10N of fiber tension that is required for composite lamination.

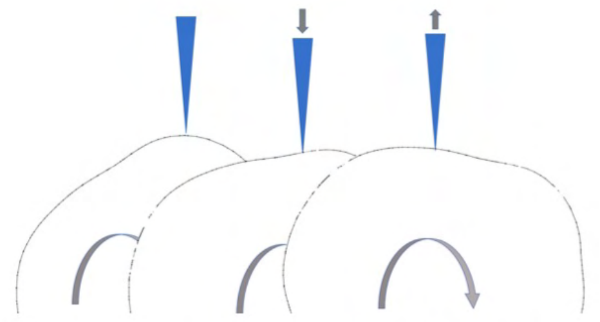
Degrees of Freedom in the AFP Prototype



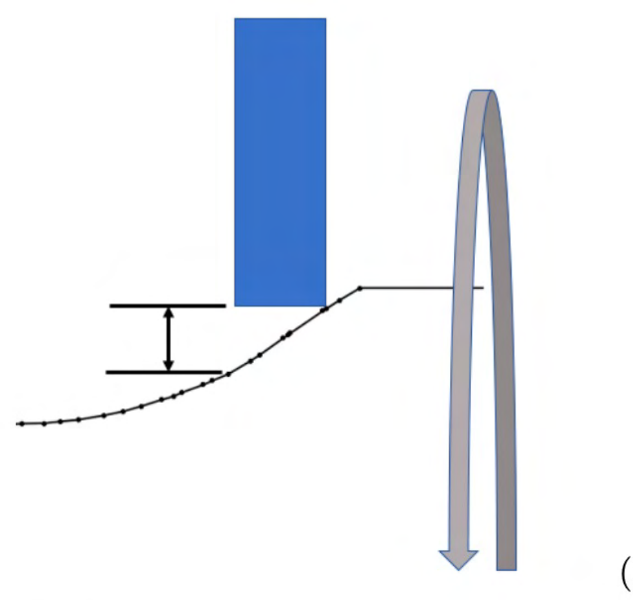
Degrees of Freedom Necessary to Traverse the Socket Geometry



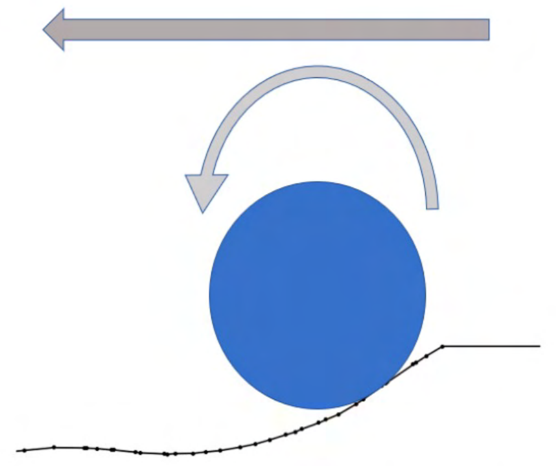
(A) Socket traversal along the Z axis. Requires motion in Z and Y direction



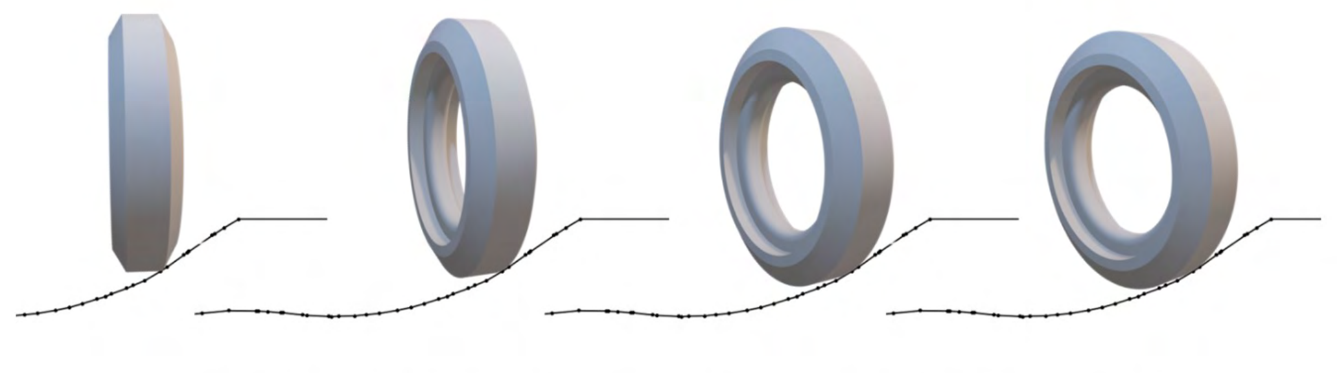
(B) Socket traversal around socket requires motion in Y and rotation about Z



(C) Gap between roller and socket surface Roller traversing surface in Z direction



(D) Roller traversing surface along Z direction



(E) Roller to surface gap shrinks as roller is rotated about the Y axis

The Traditional Socket Fabrication Process

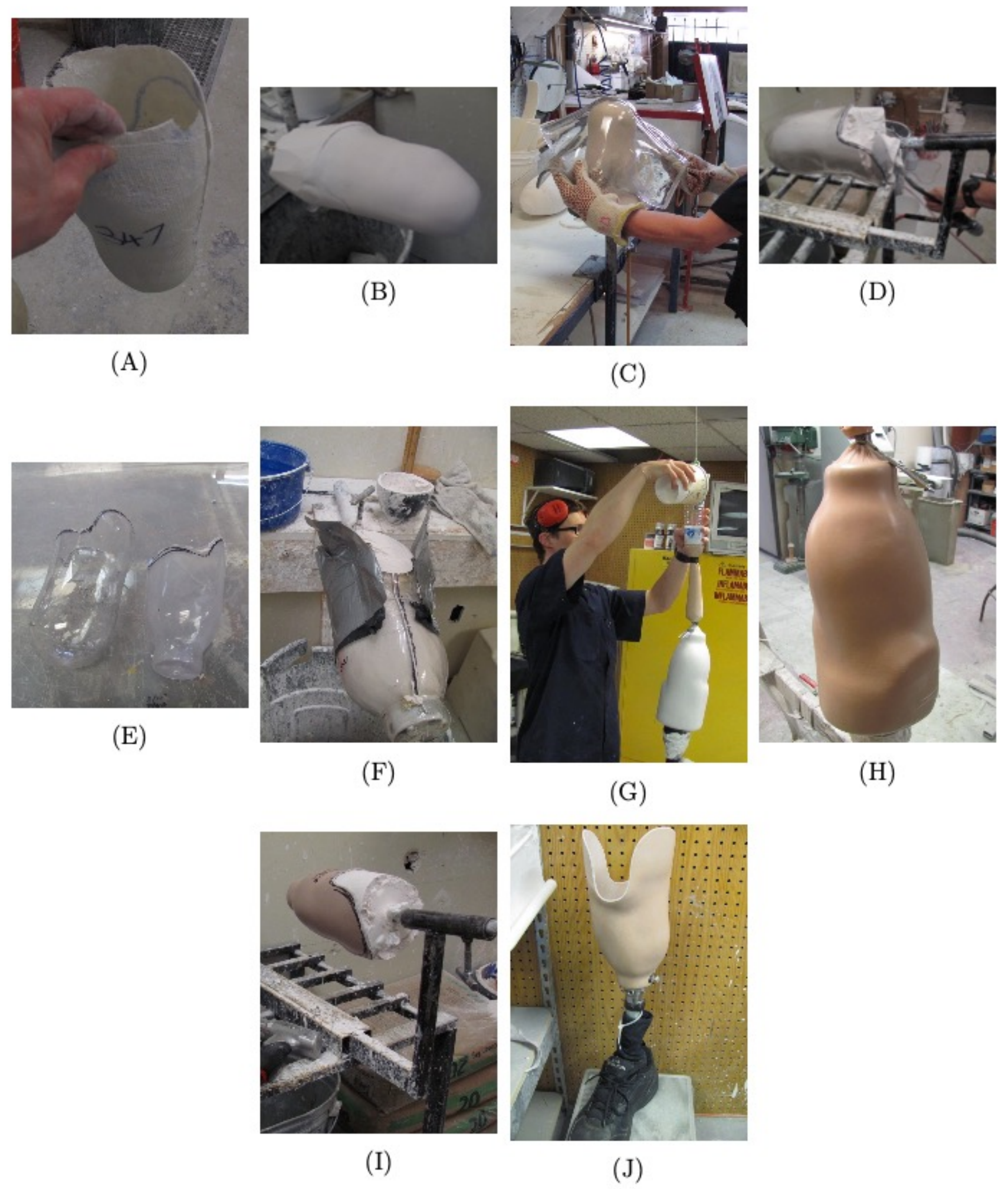


Figure 1-2: The abbreviated socket building process. A) Cast of wearer. B) Positive plaster mold. (C) Forming a temporary check socket. D) Destroying the original mold. E) The plastic check socket. F) Filling the check socket with plaster, and cutting the check socket in half to free the mold. G) Pouring in the resin. H) Massaging down the resin. I) Full wet-out of socket. J) Cut lines added. Time to destroy and remove plaster. K) Finishing the socket. L) The final socket. Taken from [2]

Broken 3D Printed Socket

To test the sockets designed by Biomech’s computational design framework the lab was 3D printing test sockets. They were never safe enough to leave the lab because they would eventually break. However, we felt they were sufficient for in-lab testing. Unfortunately, during one subject test a socket broke! This socket broken socket motivated research into new socket fabrication methods.

Master’s Thesis: From Analysis to Design

Process:

Research
  - Socket fabrication methods
  - Composite layup methods
  - Automated fiber placement machines

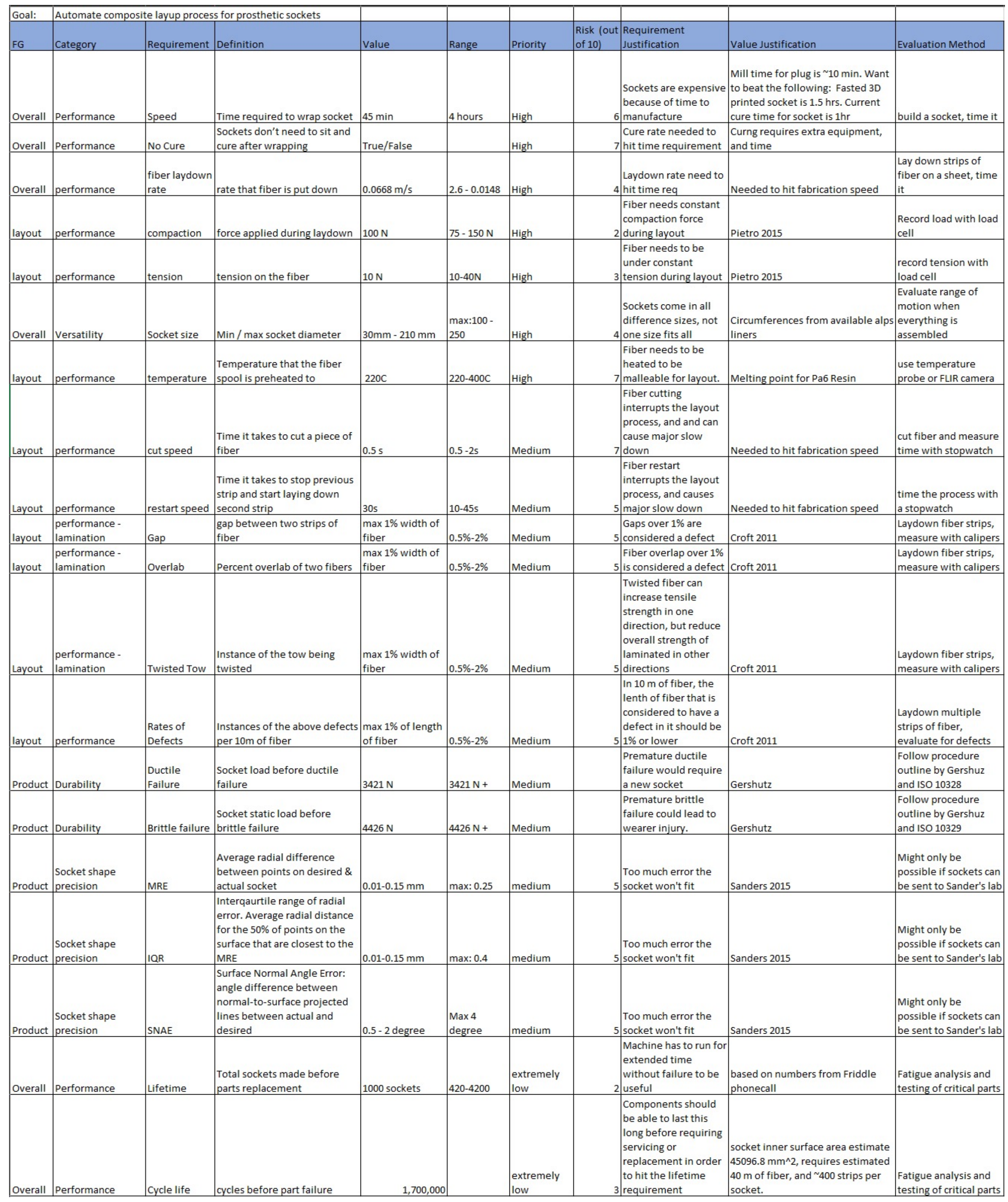
Analysis
  - Determine AFP Functional Requirements
  - Develop personal python modeling toolbox
  - Calculate machine and component performance

Design
  - Master Sketch
  - “Rough out” as much of system as possible
  - Design components
  - Source off-the-shelf parts
  - Verify parts meet performance spec
  - Iterate
  - Prep subsystem for fabrication

Build
  - Ordered custom parts from Manufacturers
  - Machined additional components in campus shop
  - Assemble in apartment
  - Test
  - Iterate if necessary
  - Move to next subsystem

System Functional Requirements

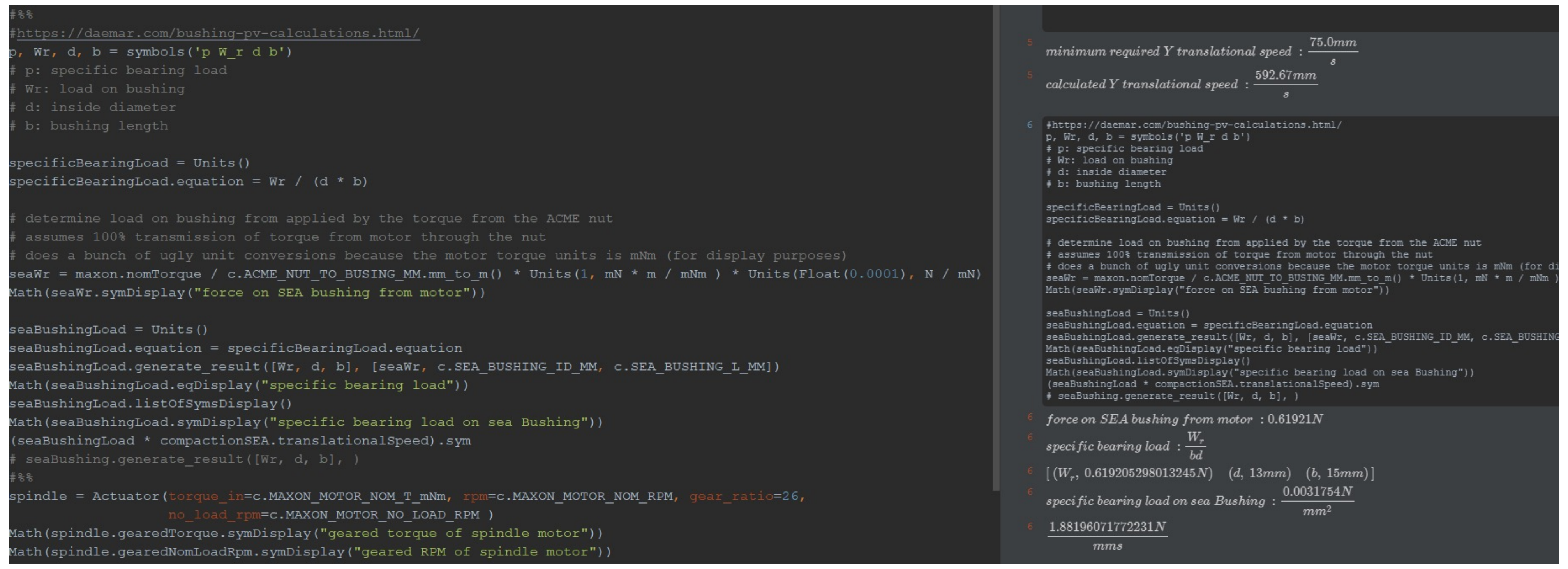
(zoom in for detail)



Goal:	Automate composite layup process for prosthetic sockets									
FG	Category	Requirement	Definition	Value	Range	Priority	Risk (out of 10)	Requirement Justification	Value Justification	Evaluation Method
Overall	Performance	Speed	Time required to wrap socket	45 min	4 hours	High	6	Sockets are expensive because of time to manufacture	Mill time for plug is ~10 min. Want to beat the following: Fasted 3D printed socket is 1.5 hrs. Current cure time for socket is 1hr	build a socket, time it
Overall	Performance	No Cure	Sockets don’t need to sit and cure after wrapping	True/False		High	7	Cure rate needed to hit time requirement	Curng requires extra equipment, and time	
Overall	performance	fiber laydown rate	rate that fiber is put down	0.0668 m/s	2.6 - 0.0148	High	4	Laydown rate need to hit time req	Needed to hit fabrication speed	Lay down strips of fiber on a sheet, time it
layout	performance	compaction	force applied during laydown	100 N	75 - 150 N	High	2	Fiber needs constant compaction force during layout	Pietro 2015	Record load with load cell
layout	performance	tension	tension on the fiber	10 N	10-40N	High	3	Fiber needs to be under constant tension during layout	Pietro 2015	record tension with load cell
Overall	Versatility	Socket size	Min / max socket diameter	30mm - 210 mm	max:100 - 250	High	4	Sockets come in all difference sizes, not one size fits all	Circumferences from available alps liners	Evaluate range of motion when everything is assembled
layout	performance	temperature	Temperature that the fiber spool is preheated to	220C	220-400C	High	7	Fiber needs to be heated to be malleable for layout.	Melting point for Pa6 Resin	use temperature probe or FLIR camera
Layout	performance	cut speed	Time it takes to cut a piece of fiber	0.5 s	0.5 -2s	Medium	7	Fiber cutting interrupts the layout process, and and can cause major slow down	Needed to hit fabrication speed	cut fiber and measure time with stopwatch
Layout	performance	restart speed	Time it takes to stop previous strip and start laying down second strip	30s	10-45s	Medium	5	Fiber restart interrupts the layout process, and causes major slow down	Needed to hit fabrication speed	time the process with a stopwatch
layout	performance - lamination	Gap	gap between two strips of fiber	max 1% width of fiber	0.5%-2%	Medium	5	Gaps over 1% are considered a defect	Croft 2011	Laydown fiber strips, measure with calipers
layout	performance - lamination	Overlab	Percent overlab of two fibers	max 1% width of fiber	0.5%-2%	Medium	5	Fiber overlap over 1% is considered a defect	Croft 2011	Laydown fiber strips, measure with calipers
Layout	performance - lamination	Twisted Tow	Instance of the tow being twisted	max 1% width of fiber	0.5%-2%	Medium	5	Twisted fiber can increase tensile strength in one direction, but reduce overall strength of laminated in other directions	Croft 2011	Laydown fiber strips, measure with calipers
layout	performance	Rates of Defects	Instances of the above defects per 10m of fiber	max 1% of length of fiber	0.5%-2%	Medium	5	In 10 m of fiber, the lenth of fiber that is considered to have a defect in it should be 1% or lower	Croft 2011	Laydown multiple strips of fiber, evaluate for defects
Product	Durability	Ductile Failure	Socket load before ductile failure	3421 N	3421 N +	Medium		Premature ductile failure would require a new socket	Gershutz	Follow procedure outline by Gershuz and ISO 10328
Product	Durability	Brittle failure	Socket static load before brittle failure	4426 N	4426 N +	Medium		Premature brittle failure could lead to wearer injury.	Gershutz	Follow procedure outline by Gershuz and ISO 10329
Product	Socket shape precision	MRE	Average radial difference between points on desired & actual socket	0.01-0.15 mm	max: 0.25	medium	5	Too much error the socket won't fit	Sanders 2015	Might only be possible if sockets can be sent to Sander's lab
Product	Socket shape precision	IQR	Interqaurtile range of radial error. Average radial distance for the 50% of points on the surface that are closest to the MRE	0.01-0.15 mm	max: 0.4	medium	5	Too much error the socket won't fit	Sanders 2015	Might only be possible if sockets can be sent to Sander's lab
Product	Socket shape precision	SNAE	Surface Normal Angle Error: angle difference between normal-to-surface projected lines between actual and desired	0.5 - 2 degree	Max 4 degree	medium	5	Too much error the socket won't fit	Sanders 2015	Might only be possible if sockets can be sent to Sander's lab
Overall	Performance	Lifetime	Total sockets made before parts replacement	1000 sockets	420-4200	extremely low	2	Machine has to run for extended time without failure to be useful	based on numbers from Friddle phonecall	Fatigue analysis and testing of critical parts
Overall	Performance	Cycle life	cycles before part failure	1,700,000		extremely low	3	Components should be able to last this long before requiring servicing or replacement in order to hit the lifetime requirement	socket inner surface area estimate 45096.8 mm^2, requires estimated 40 m of fiber, and ~400 strips per socket.	Fatigue analysis and testing of critical parts

Python Modeling Environment

(Zoom in for detail)



```
#%%
#https://daemar.com/bushing-pv-calculations.html/
p, Wr, d, b = symbols('p W_r d b')
# p: specific bearing load
# Wr: load on bushing
# d: inside diameter
# b: bushing length

specificBearingLoad = Units()
specificBearingLoad.equation = Wr / (d * b)

# determine load on bushing from applied by the torque from the ACME nut
# assumes 100% transmission of torque from motor through the nut
# does a bunch of ugly unit conversions because the motor torque units is mNm (for display purposes)
seaWr = maxon.nomTorque / c.ACME_NUT_TO_BUSING_MM.mm_to_m() * Units(1, mN * m / mNm ) * Units(Float(0.0001), N / mN)
Math(seaWr.symDisplay("force on SEA bushing from motor"))

seaBushingLoad = Units()
seaBushingLoad.equation = specificBearingLoad.equation
seaBushingLoad.generate_result([Wr, d, b], [seaWr, c.SEA_BUSHING_ID_MM, c.SEA_BUSHING_L_MM])
Math(seaBushingLoad.eqDisplay("specific bearing load"))
seaBushingLoad.listOfSymsDisplay()
Math(seaBushingLoad.symDisplay("specific bearing load on sea Bushing"))
(seaBushingLoad * compactionSEA.translationalSpeed).sym
# seaBushing.generate_result([Wr, d, b], )
#%%
spindle = Actuator(torque_in=c.MAXON_MOTOR_NOM_T_mNm, rpm=c.MAXON_MOTOR_NOM_RPM, gear_ratio=26,
                   no_load_rpm=c.MAXON_MOTOR_NO_LOAD_RPM )
Math(spindle.gearedTorque.symDisplay("geared torque of spindle motor"))
Math(spindle.gearedNomLoadRpm.symDisplay("geared RPM of spindle motor"))
```

5 $minimum\ required\ Y\ translational\ speed\ : \frac{75.0mm}{s}$

5 $calculated\ Y\ translational\ speed\ : \frac{592.67mm}{s}$

```
#https://daemar.com/bushing-pv-calculations.html/
p, Wr, d, b = symbols('p W_r d b')
# p: specific bearing load
# Wr: load on bushing
# d: inside diameter
# b: bushing length

specificBearingLoad = Units()
specificBearingLoad.equation = Wr / (d * b)

# determine load on bushing from applied by the torque from the ACME nut
# assumes 100% transmission of torque from motor through the nut
# does a bunch of ugly unit conversions because the motor torque units is mNm (for di
seaWr = maxon.nomTorque / c.ACME_NUT_TO_BUSING_MM.mm_to_m() * Units(1, mN * m / mNm )
Math(seaWr.symDisplay("force on SEA bushing from motor"))

seaBushingLoad = Units()
seaBushingLoad.equation = specificBearingLoad.equation
seaBushingLoad.generate_result([Wr, d, b], [seaWr, c.SEA_BUSHING_ID_MM, c.SEA_BUSHING
Math(seaBushingLoad.eqDisplay("specific bearing load"))
seaBushingLoad.listOfSymsDisplay()
Math(seaBushingLoad.symDisplay("specific bearing load on sea Bushing"))
(seaBushingLoad * compactionSEA.translationalSpeed).sym
# seaBushing.generate_result([Wr, d, b], )
```

6 $force\ on\ SEA\ bushing\ from\ motor\ : 0.61921N$

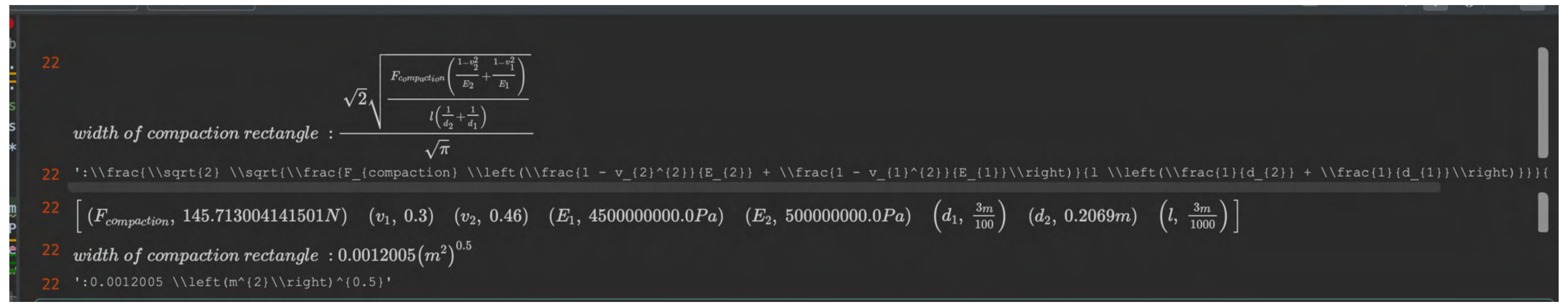
6 $specific\ bearing\ load\ : \frac{W_r}{bd}$

6 $[(W_r,\ 0.619205298013245N)\quad (d,\ 13mm)\quad (b,\ 15mm)]$

6 $specific\ bearing\ load\ on\ sea\ Bushing\ : \frac{0.0031754N}{mm^2}$

6 $\frac{1.88196071772231N}{mms}$

Calculating the Hertzian contact Rectangle width between two cylinders



22 $$width\ of\ compaction\ rectangle\ : \frac{\sqrt{2}\sqrt{\frac{F_{compaction}\left(\frac{1-v_2^2}{E_2}+\frac{1-v_1^2}{E_1}\right)}{l\left(\frac{1}{d_2}+\frac{1}{d_1}\right)}}}{\sqrt{\pi}}$$

```
22 ':\\frac{\\sqrt{2} \\sqrt{\\frac{F_{compaction} \\left(\\frac{1 - v_{2}^{2}}{E_{2}} + \\frac{1 - v_{1}^{2}}{E_{1}}\\right)}{l \\left(\\frac{1}{d_{2}} + \\frac{1}{d_{1}}\\right)}}}{
```

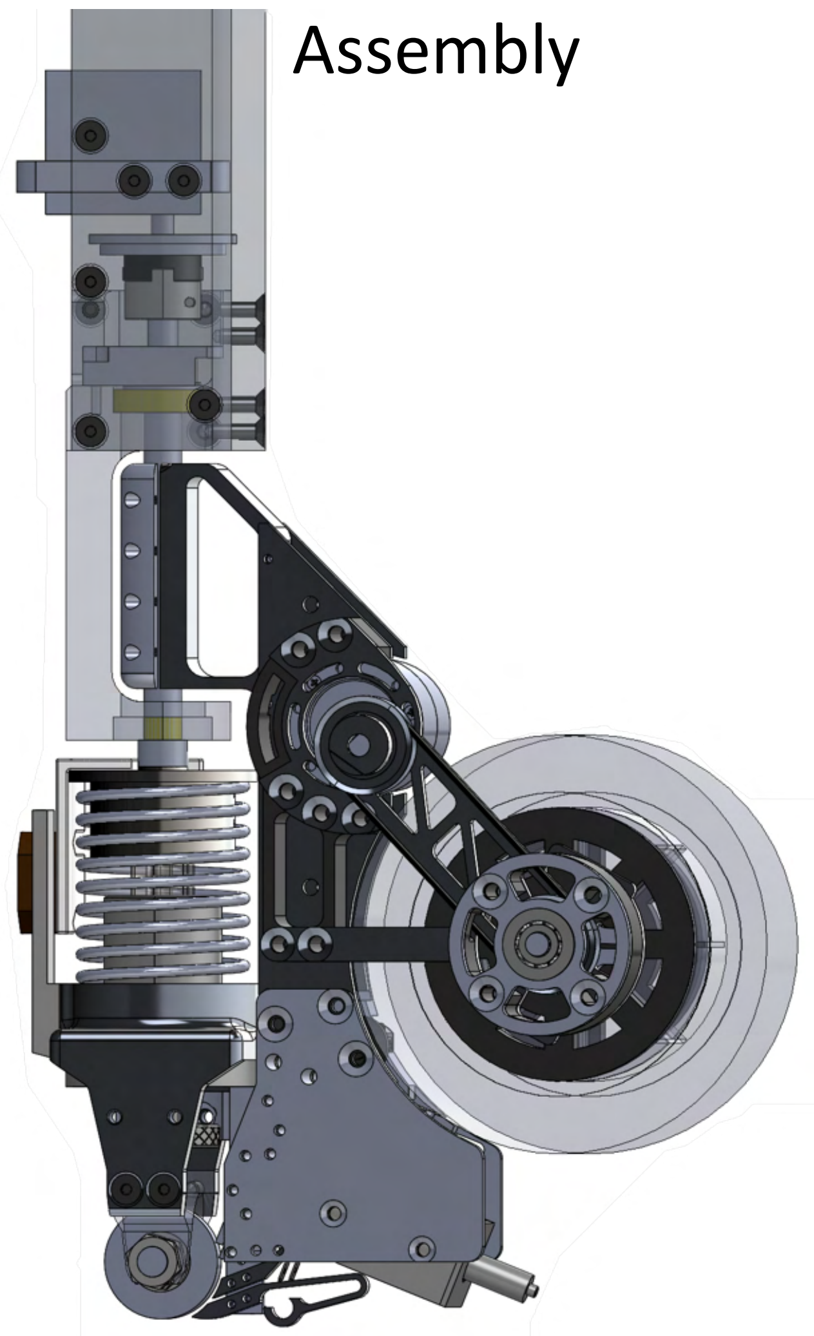
22 $\left[(F_{compaction},\ 145.713004141501N)\quad (v_1,\ 0.3)\quad (v_2,\ 0.46)\quad (E_1,\ 4500000000.0Pa)\quad (E_2,\ 500000000.0Pa)\quad \left(d_1,\ \frac{3m}{100}\right)\quad (d_2,\ 0.2069m)\quad \left(l,\ \frac{3m}{1000}\right)\right]$

22 $width\ of\ compaction\ rectangle\ : 0.0012005\left(m^2\right)^{0.5}$

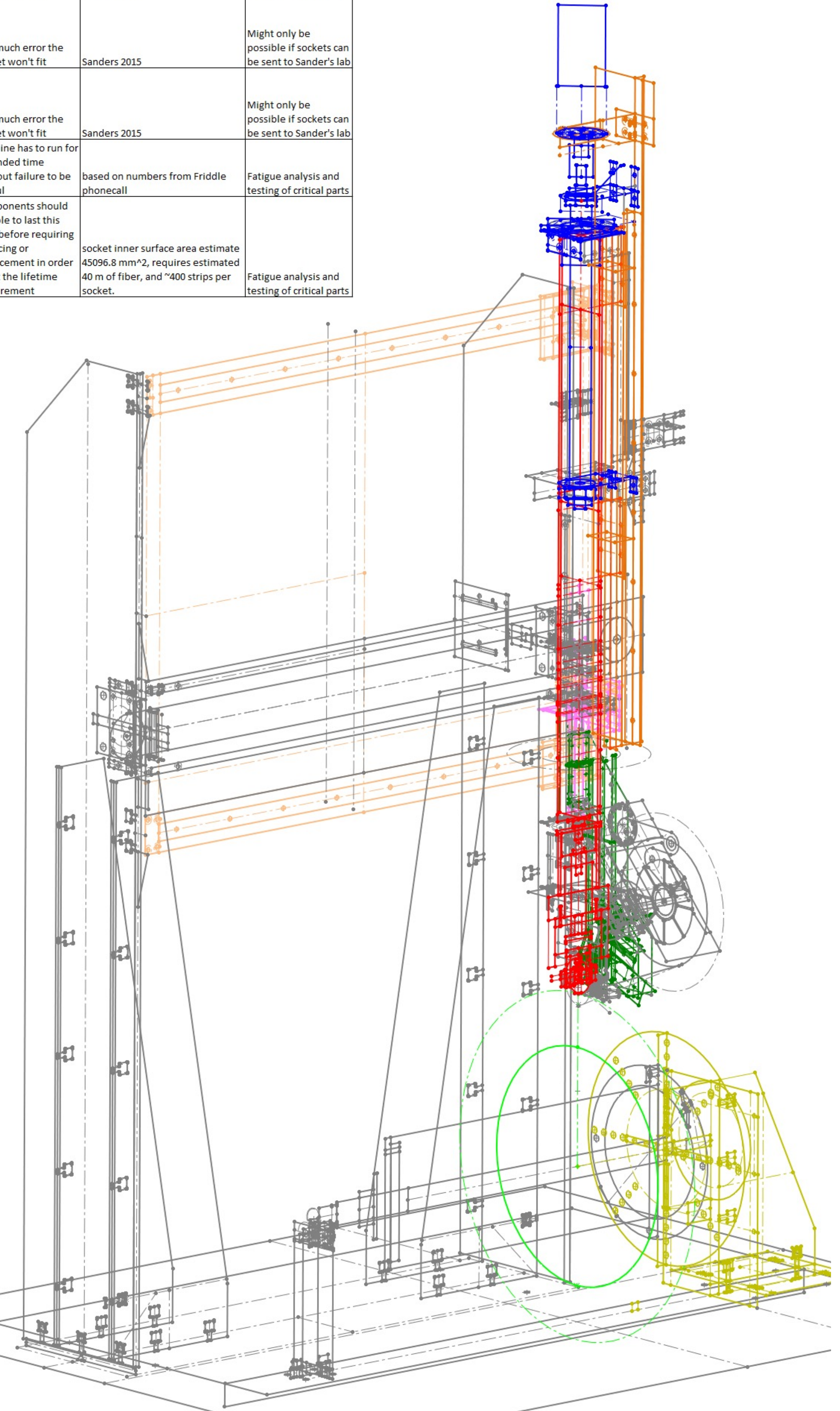
```
22 ':0.0012005 \\left(m^{2}\\right)^{0.5}'
```

I started developing my own modeling toolbox because I was dissatisfied with Matlab and Excel for mechanical design. I have three goals for my modeling environment: easily editable equations, outputs that included not only the numerical solution but also the mathematical equations used, and the ability to include physical units in the equations. My secondary goals were that the software could output the equations in Latex syntax for use in the thesis and that I could incorporate equation solutions into the software library that runs the AFP machine.

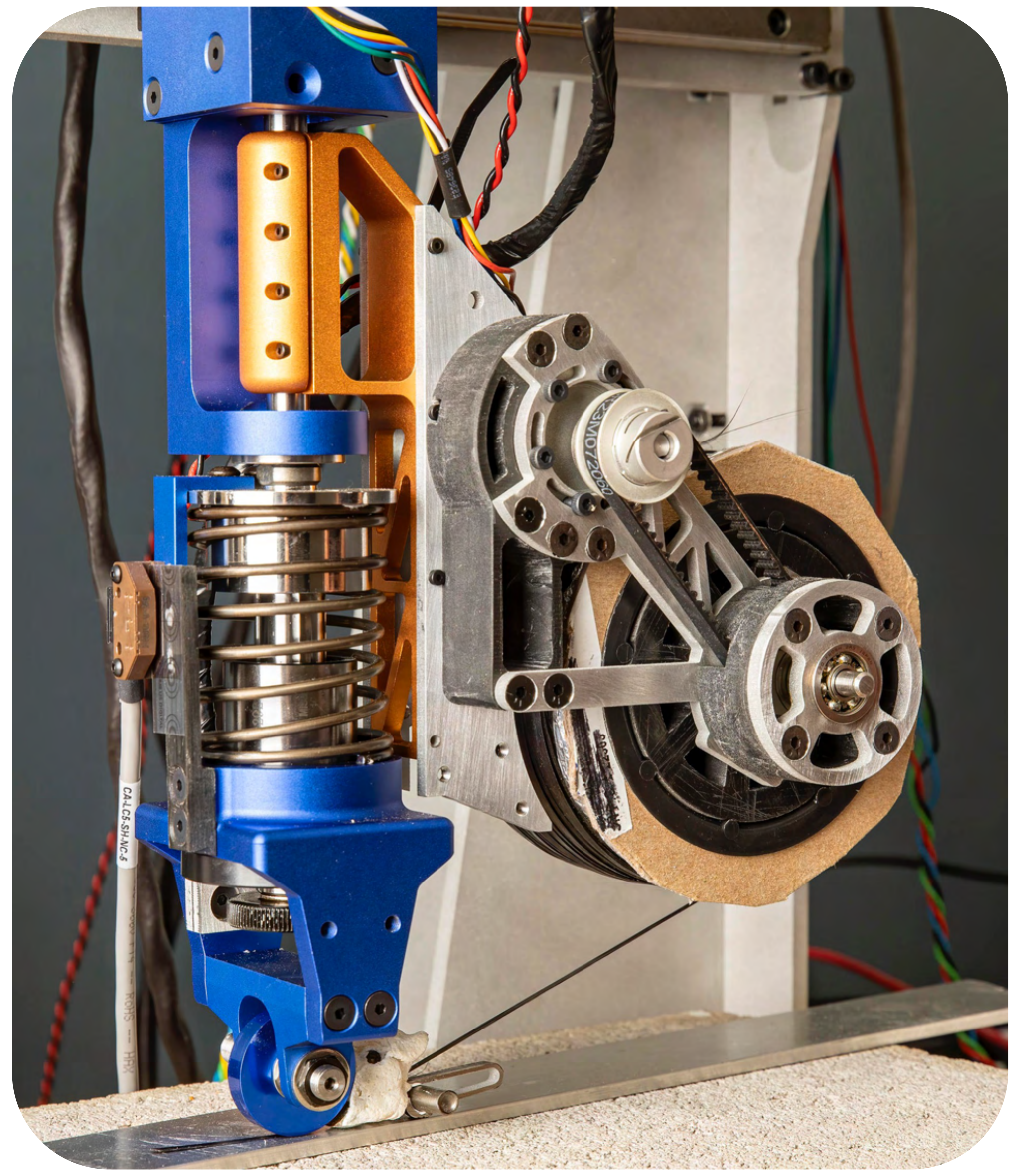
CAD of End Effector Assembly



AFP Assembly Master Sketch



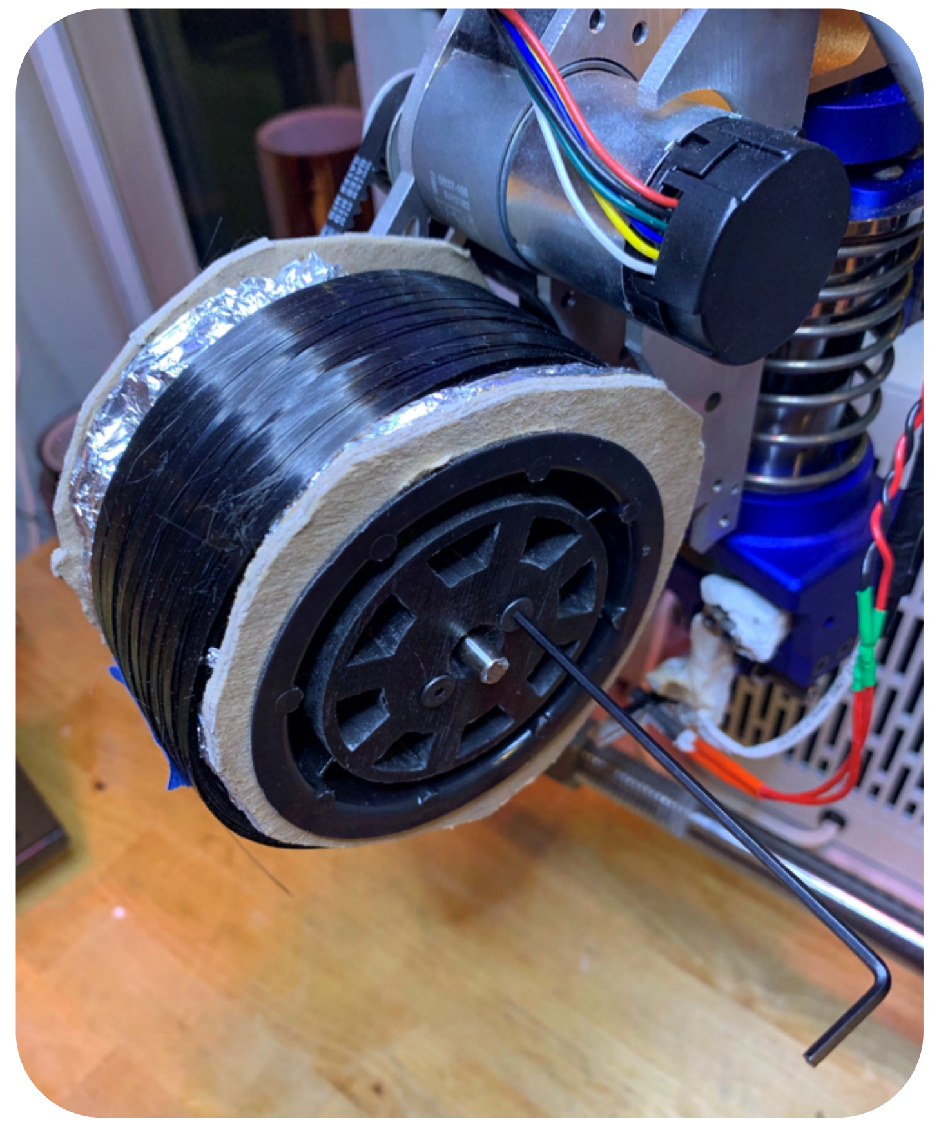
End Effector Assembled:
Series Elastic Compaction Actuator
Fiber Management
Fiber Orientation DOF



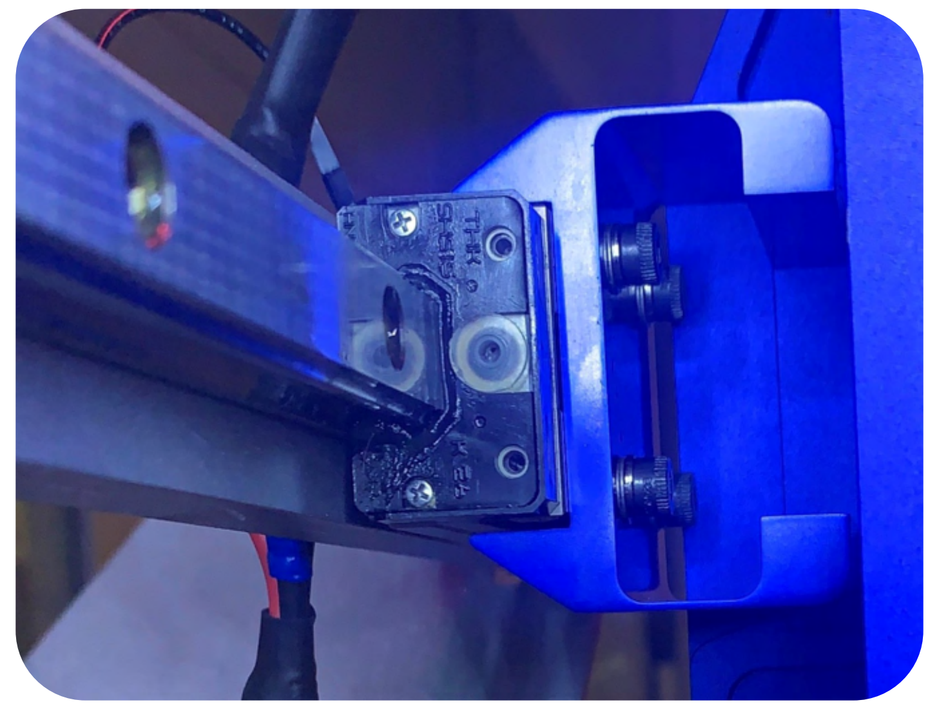
Series Elastic Actuator Components

A Few Closeups

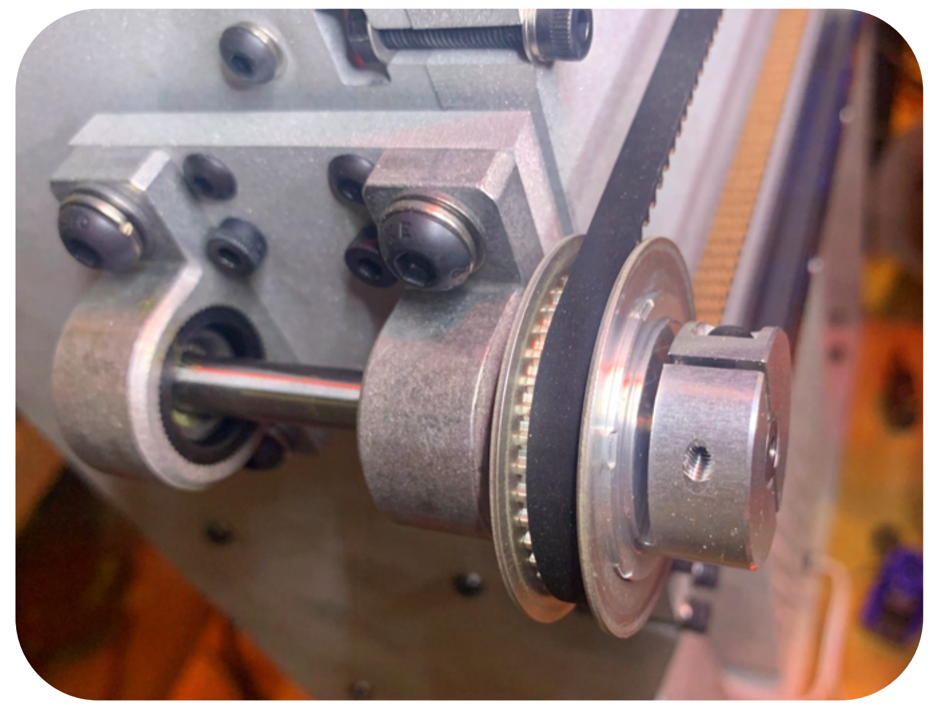
Remove 2 Screws to Replace Fiber Spool



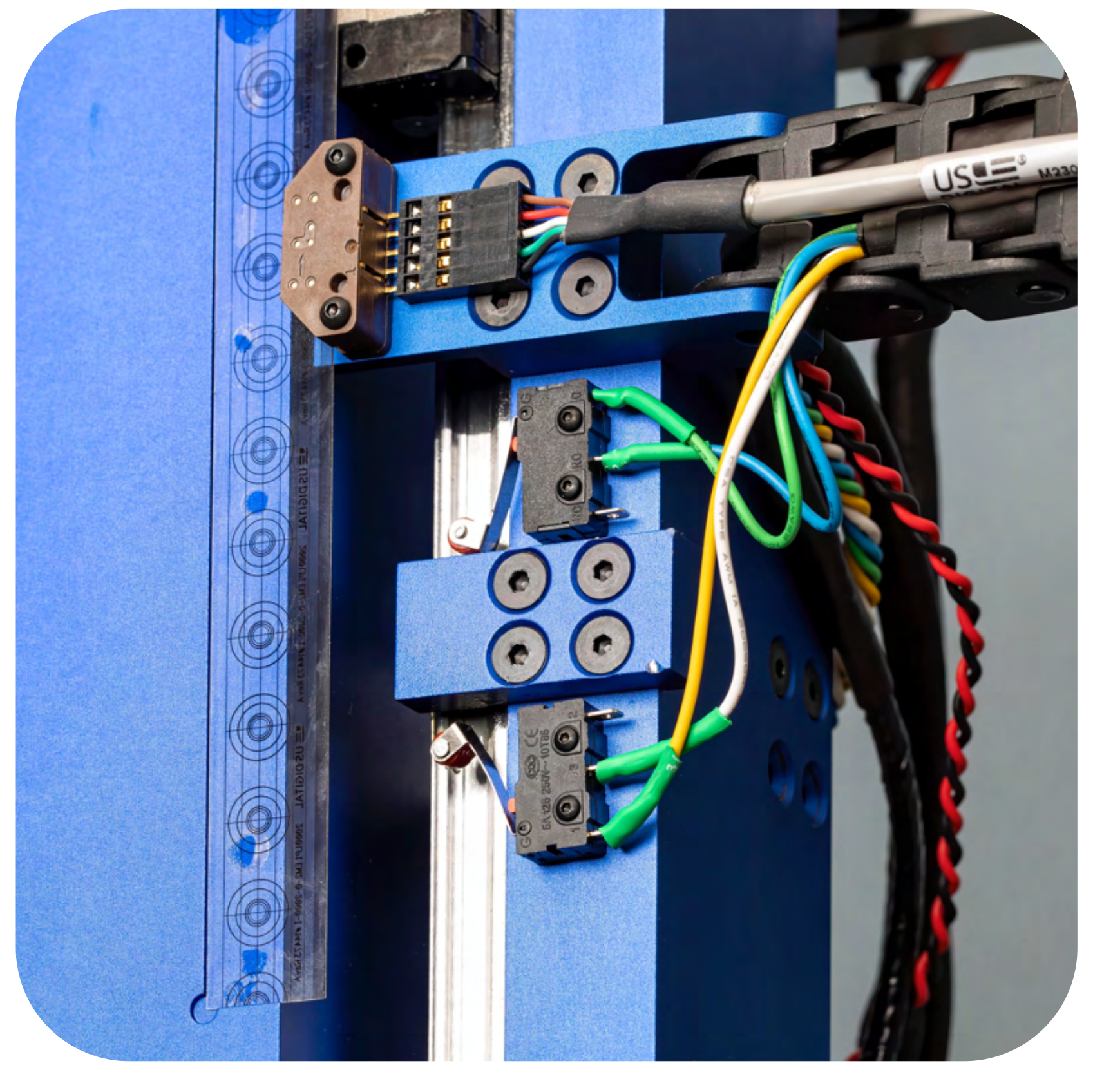
Bearing Flexure to Avoid Over-Constraint



Belt Tensioning

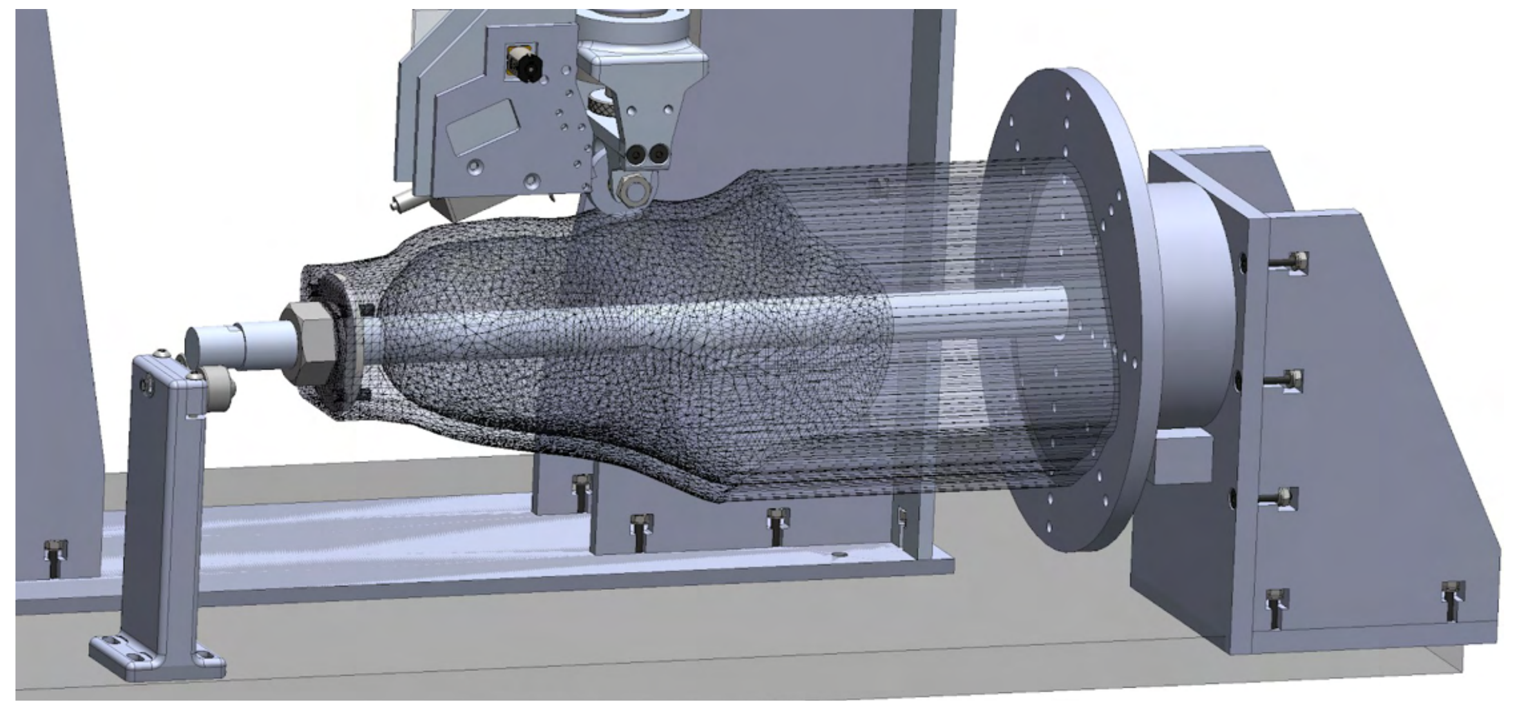


Encoder, Limit Switches, Hardstop



Workholding Support

Work Holding



Master’s Thesis: Software

Software Goals

User interacts with GUI to send actions and parameters to machine

Machine parses input

Machine acts

Updates user while acting

Finish action and wait for next command

User can cancel action if necessary

Robot Control:

Two microcontrollers, one for Series Elastic Actuator (SEA), one for the remaining DOFs

Devices run non-blocking state machine

SEA controlled with PID, separate gains for contact and non-contact states.

Tools:

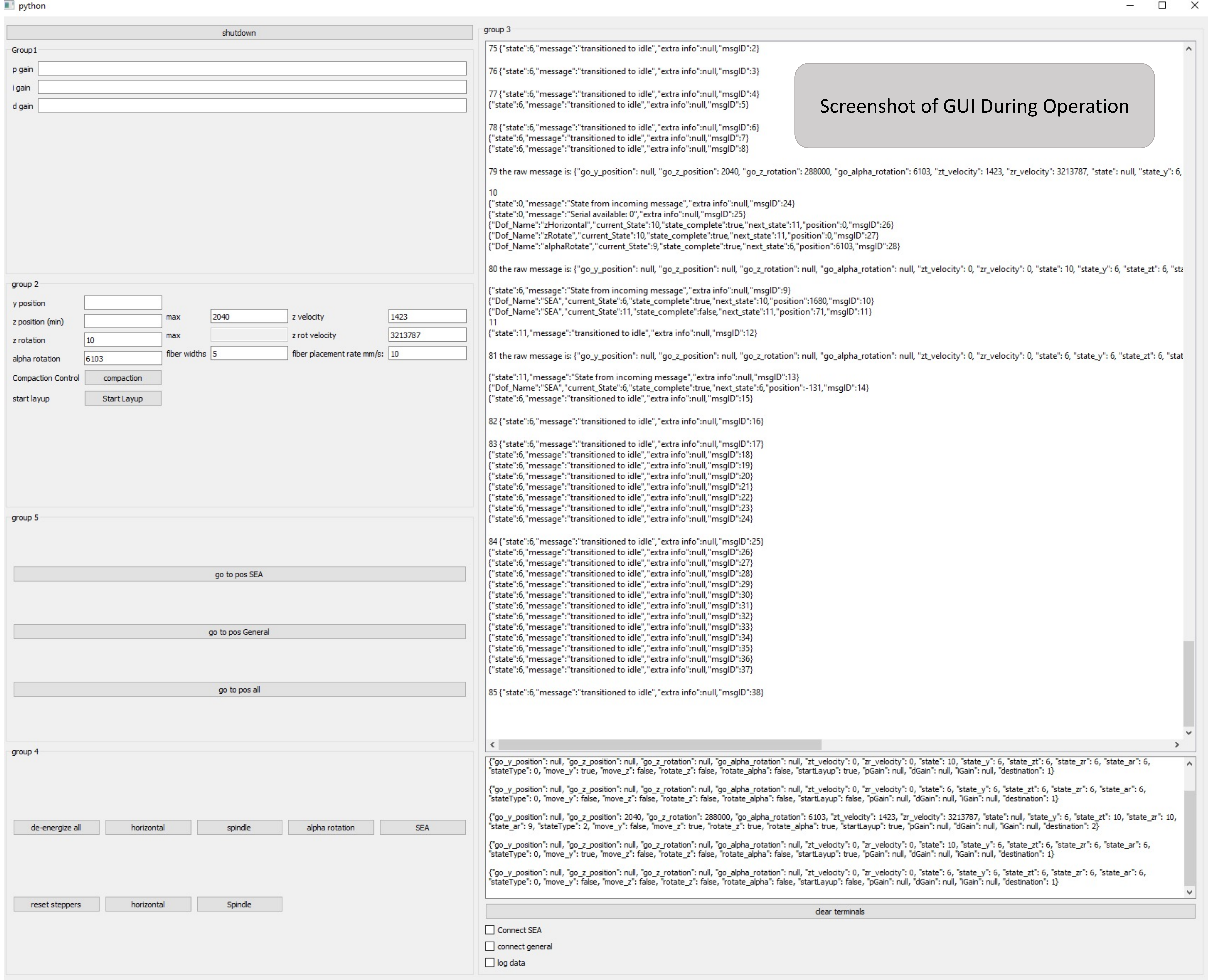
GUI: Python, PyQT

Device: Teensy, programmed with Arduino

Environment: Pycharm, Clion with PlatformIO

Github

Messages: Json



p gain

i gain

d gain

y position

z position (min)   max 2040   z velocity 1423

z rotation 10   max   z rot velocity 3213787

alpha rotation 6103   fiber widths 5   fiber placement rate mm/s: 10

Compaction Control   compaction

start layup   Start Layup

```
75 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":2}

76 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":3}

77 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":4}
{"state":6,"message":"transitioned to idle","extra info":null,"msgID":5}

78 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":6}
{"state":6,"message":"transitioned to idle","extra info":null,"msgID":7}
{"state":6,"message":"transitioned to idle","extra info":null,"msgID":8}

79 the raw message is: {"go_y_position": null, "go_z_position": 2040, "go_z_rotation": 288000, "go_alpha_rotation": 6103, "zt_velocity": 1423, "zr_velocity": 3213787, "state": null, "state_y": 6,

10
{"state":0,"message":"State from incoming message","extra info":null,"msgID":24}
{"state":0,"message":"Serial available: 0","extra info":null,"msgID":25}
{"Dof_Name":"zHorizontal","current_State":10,"state_complete":true,"next_state":11,"position":0,"msgID":26}
{"Dof_Name":"zRotate","current_State":10,"state_complete":true,"next_state":11,"position":0,"msgID":27}
{"Dof_Name":"alphaRotate","current_State":9,"state_complete":true,"next_state":6,"position":6103,"msgID":28}

80 the raw message is: {"go_y_position": null, "go_z_position": null, "go_z_rotation": null, "go_alpha_rotation": null, "zt_velocity": 0, "zr_velocity": 0, "state": 10, "state_y": 6, "state_zt": 6, "sta

{"state":6,"message":"State from incoming message","extra info":null,"msgID":9}
{"Dof_Name":"SEA","current_State":6,"state_complete":true,"next_state":10,"position":1680,"msgID":10}
{"Dof_Name":"SEA","current_State":11,"state_complete":false,"next_state":11,"position":71,"msgID":11}
11
{"state":11,"message":"transitioned to idle","extra info":null,"msgID":12}

81 the raw message is: {"go_y_position": null, "go_z_position": null, "go_z_rotation": null, "go_alpha_rotation": null, "zt_velocity": 0, "zr_velocity": 0, "state": 6, "state_y": 6, "state_zt": 6, "stat

{"state":11,"message":"State from incoming message","extra info":null,"msgID":13}
{"Dof_Name":"SEA","current_State":6,"state_complete":true,"next_state":6,"position":-131,"msgID":14}
{"state":6,"message":"transitioned to idle","extra info":null,"msgID":15}

82 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":16}

83 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":17}
{"state":6,"message":"transitioned to idle","extra info":null,"msgID":18}
{"state":6,"message":"transitioned to idle","extra info":null,"msgID":19}
{"state":6,"message":"transitioned to idle","extra info":null,"msgID":20}
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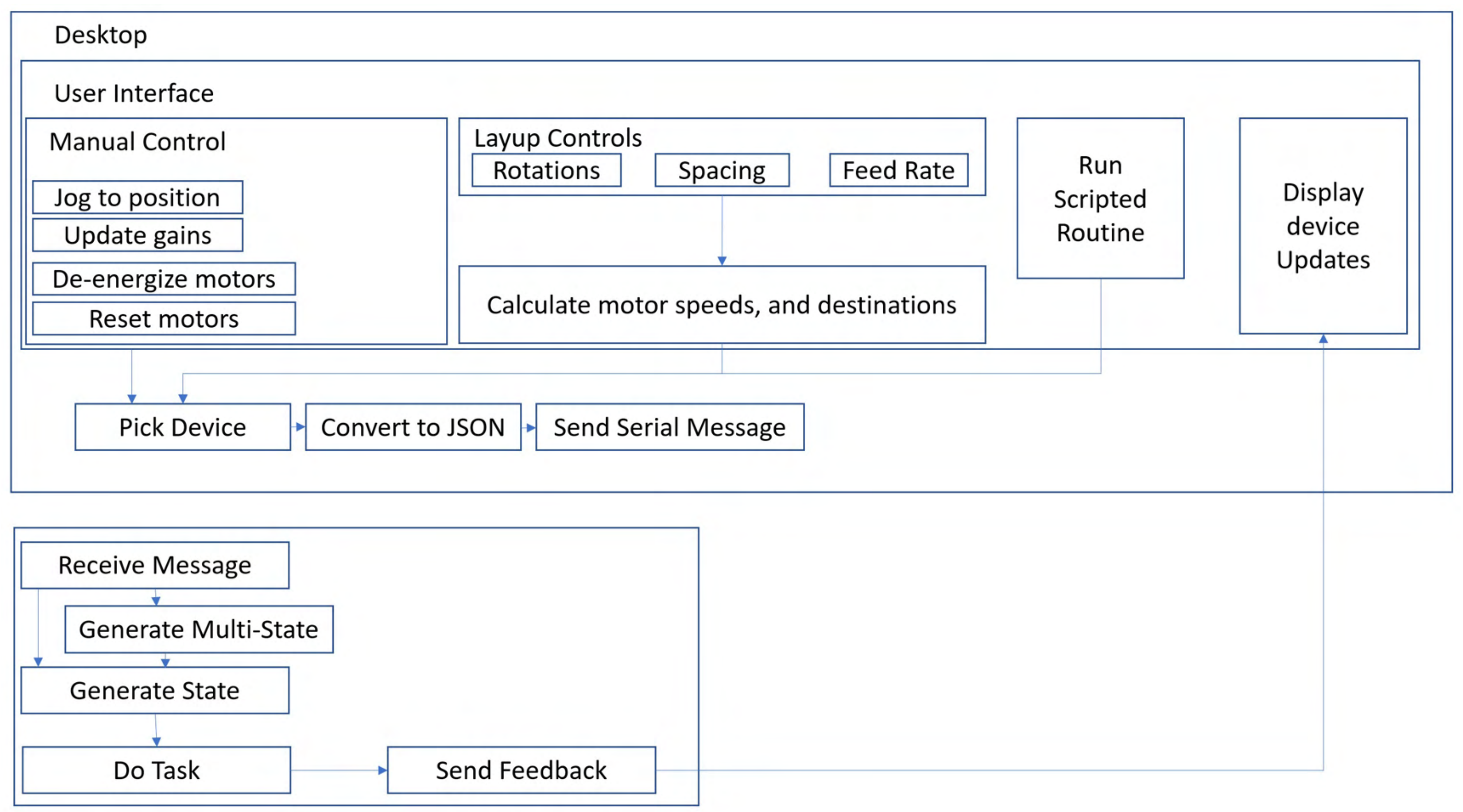
☐ Connect SEA

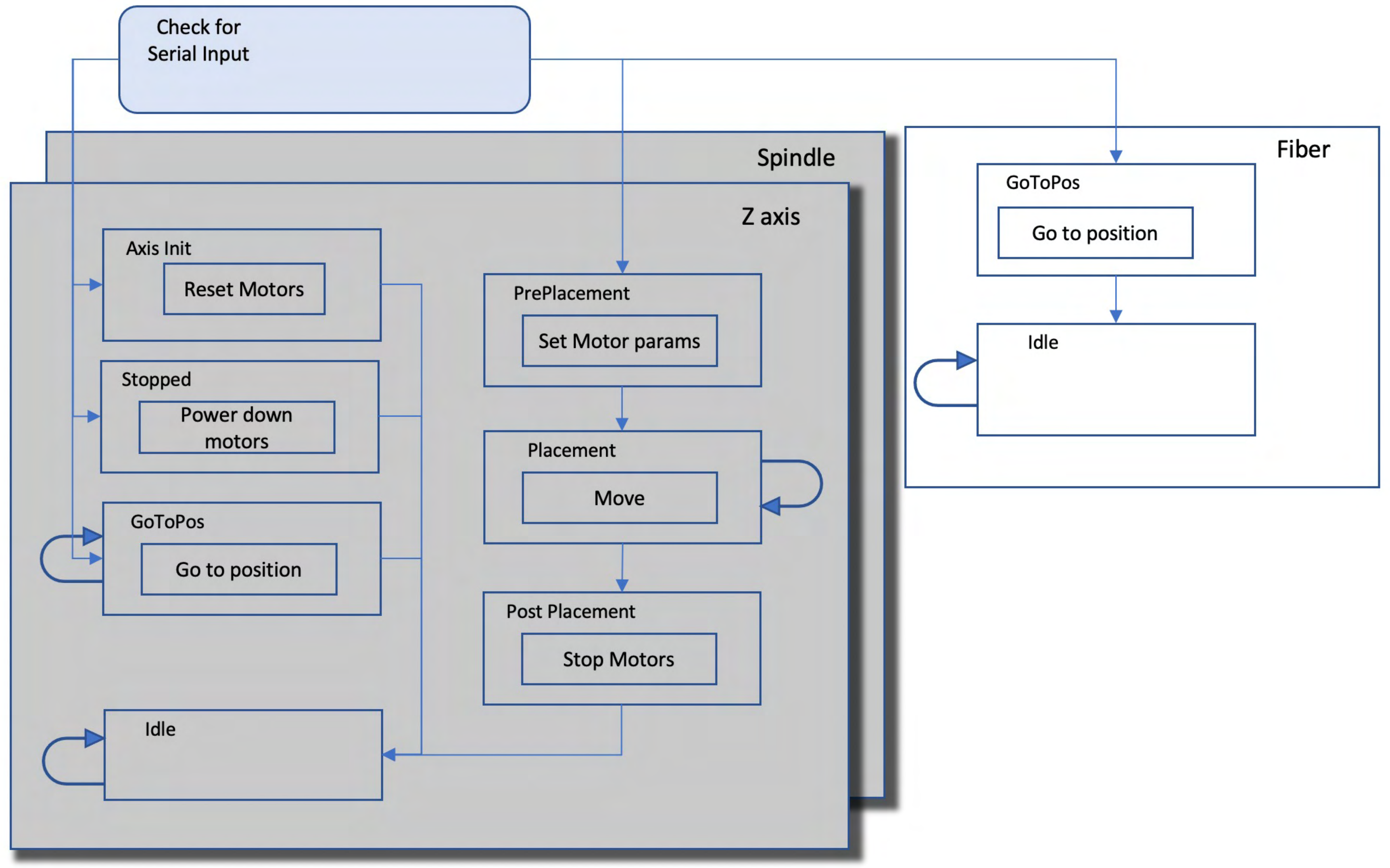
☐ connect general

☐ log data

Screenshot of GUI During Operation

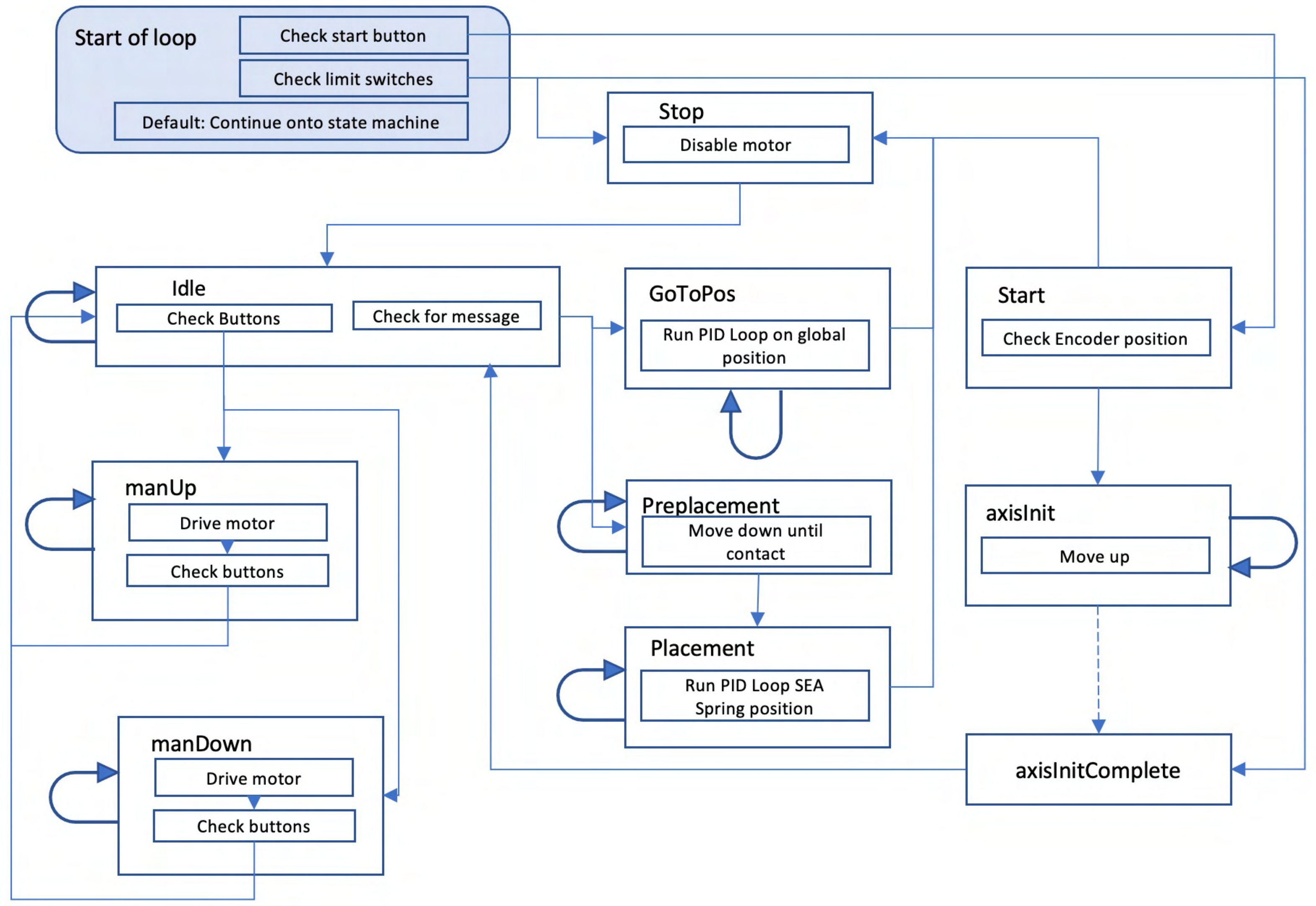
Desktop Program Software Overview





SEA Compaction State Machine

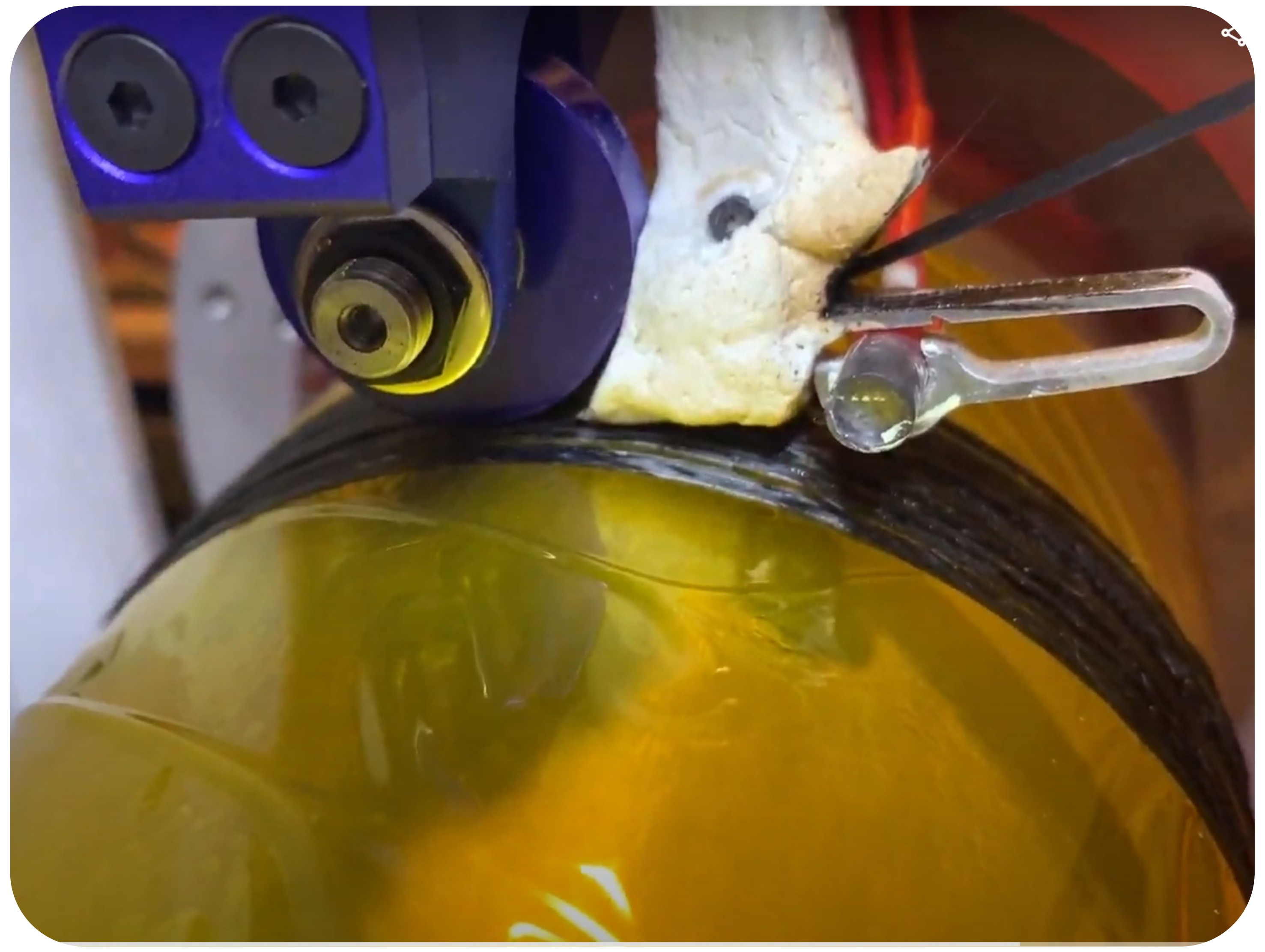
All Other DOFs State Machine



Master’s Thesis:
Testing and Evaluation

Outcome: The prototype AFP machine demonstrated compaction on non-planar surfaces necessary for fiber placement at a desktop scale.

Evaluation: The evaluation tested the machine’s performance against the Functional Requirements included the production of demonstration fiber parts, compaction load testing, structural testing of the machine, and motion control evaluation. The scope of the project did not ultimately include a complete transtibial socket.

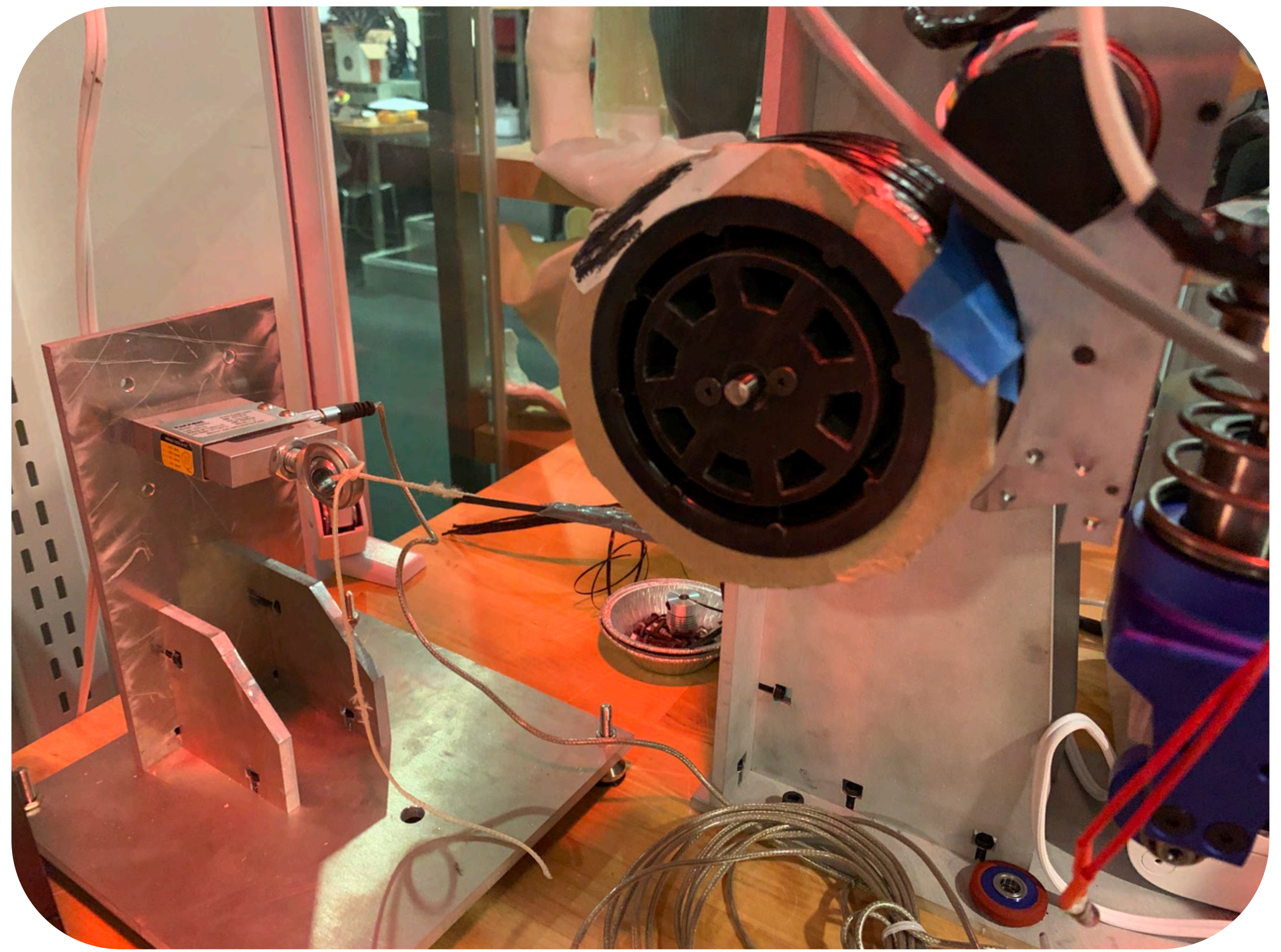


During development, the AFP machine produced lamination samples on a flat surface and a cylinder as shown in Figure 8-10. The cinder blocks were used as a sturdy raised surface as the Y axis cannot contact the table. The wrapping tests were done with an aluminum cylinder with an 114 mm diameter.3 This cylinder is a simpler shape than a transtibial socket and approximates the dimensions of many of Biomech’s trial subjects.

The flat strip tests were conducted when the Y axis, Z translational axis, and Fiber DOF could first be position controlled. The Z axis speed could not yet be adjusted, therefore the fiber feed-rate could not be adjusted. The strip produced is shown in Figure 8-10. This experiment demonstrated that the machine was capable of laminating strips together but also provided insight on many process challenges that had to be addressed

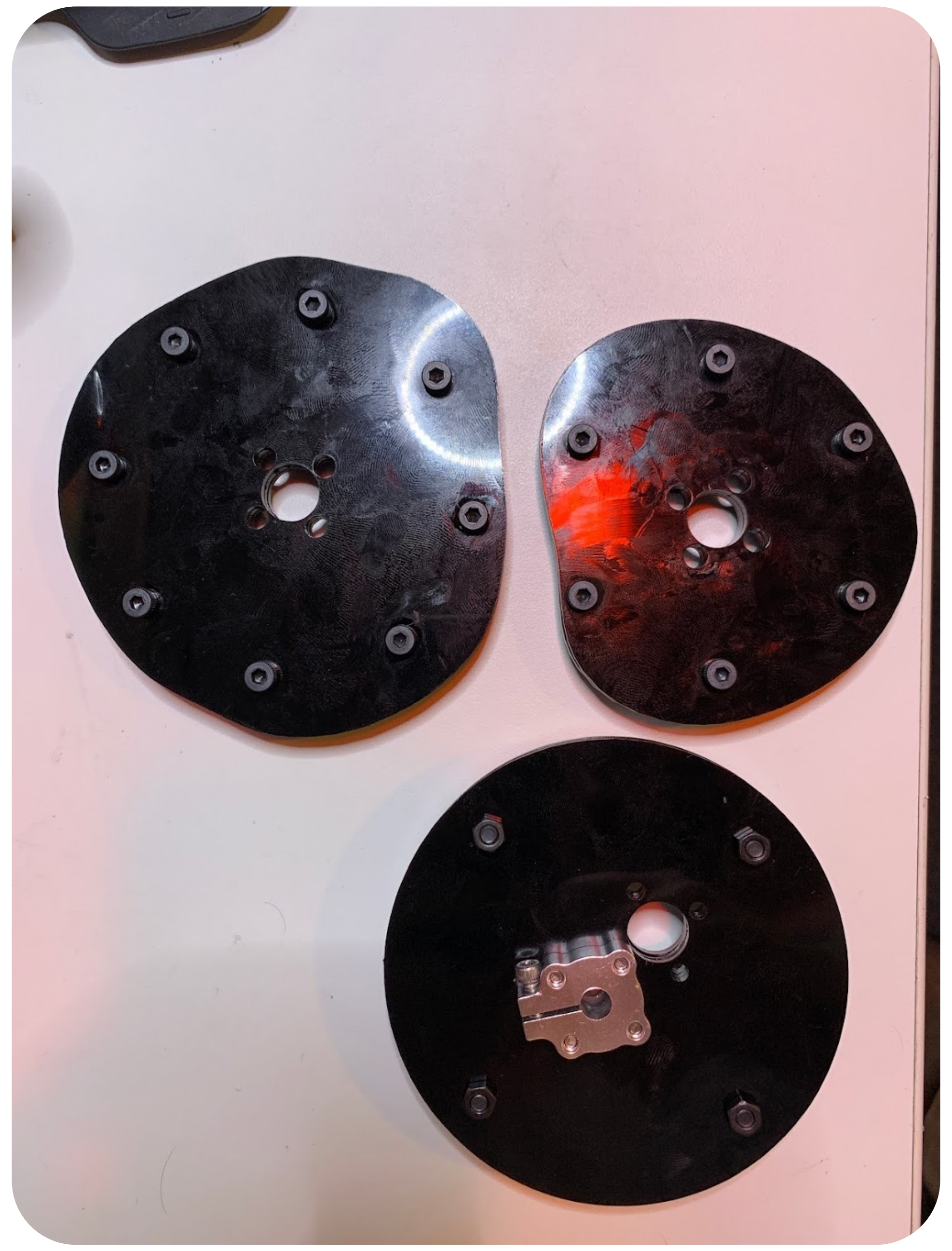
Moving to a cylinder was possible when the feeds and speeds calculations were implemented. The first test was 2mm/s feed-rate and 1 fiber-width of spacing so that adjacent fibers would be touching. The first wrapped part is shown in 8-12A. The first obvious problem with the test was that the secondary heater was not in contact with the cylinder.

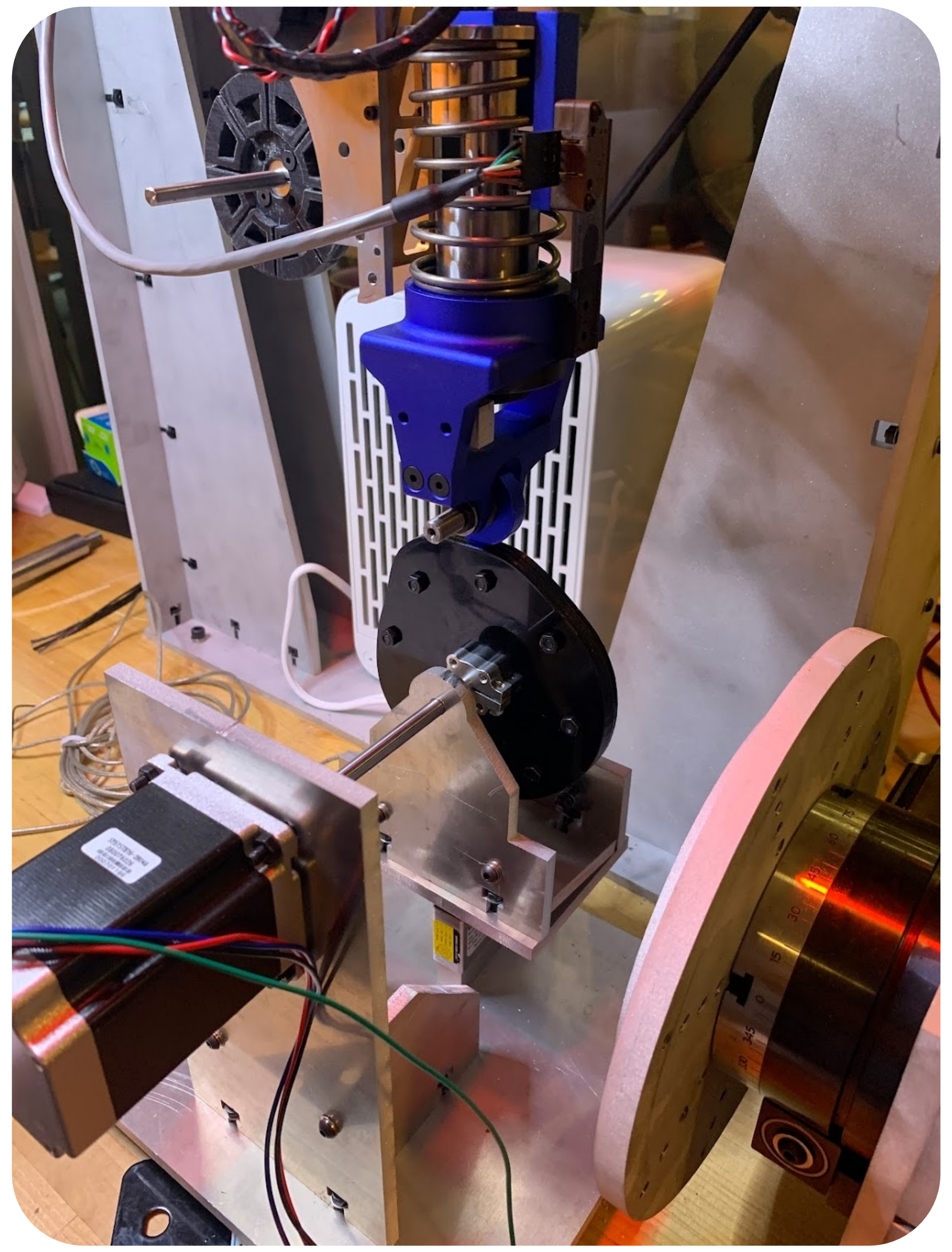
When the part had to be cut to remove it from the cylinder, the fiber still connected to the Kapton© as shown in 8-12B. When the tape was removed the fibers fell apart as shown in 8-12B. As the previously placed fibers were not being sufficiently heated, the newly placed fiber was not properly adhering to the previous layer. The test was repeated at a 1mm/s feed-rate. The parts are shown in Figure 8-13. For this test the fiber held together after being removed from the cylinder. The slower feed-rate increased the temperature of the fiber tow being placed and help to improve the adhesion. The part lamination quality could still use improvement. The material build-up on the heater, as shown earlier in 6-5, pushed the fiber tow off-center of the roller and caused the tow to twist as it was being placed.

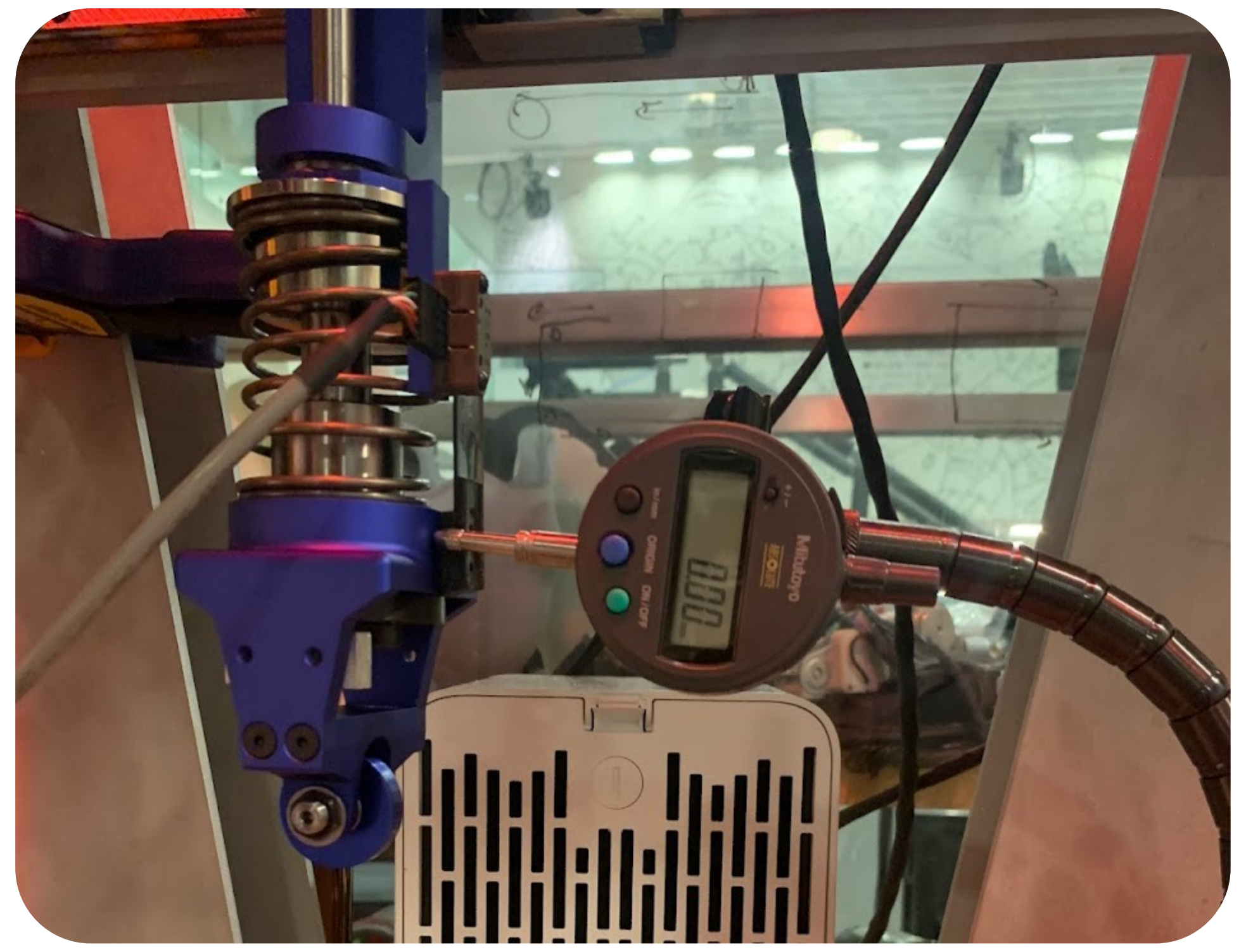


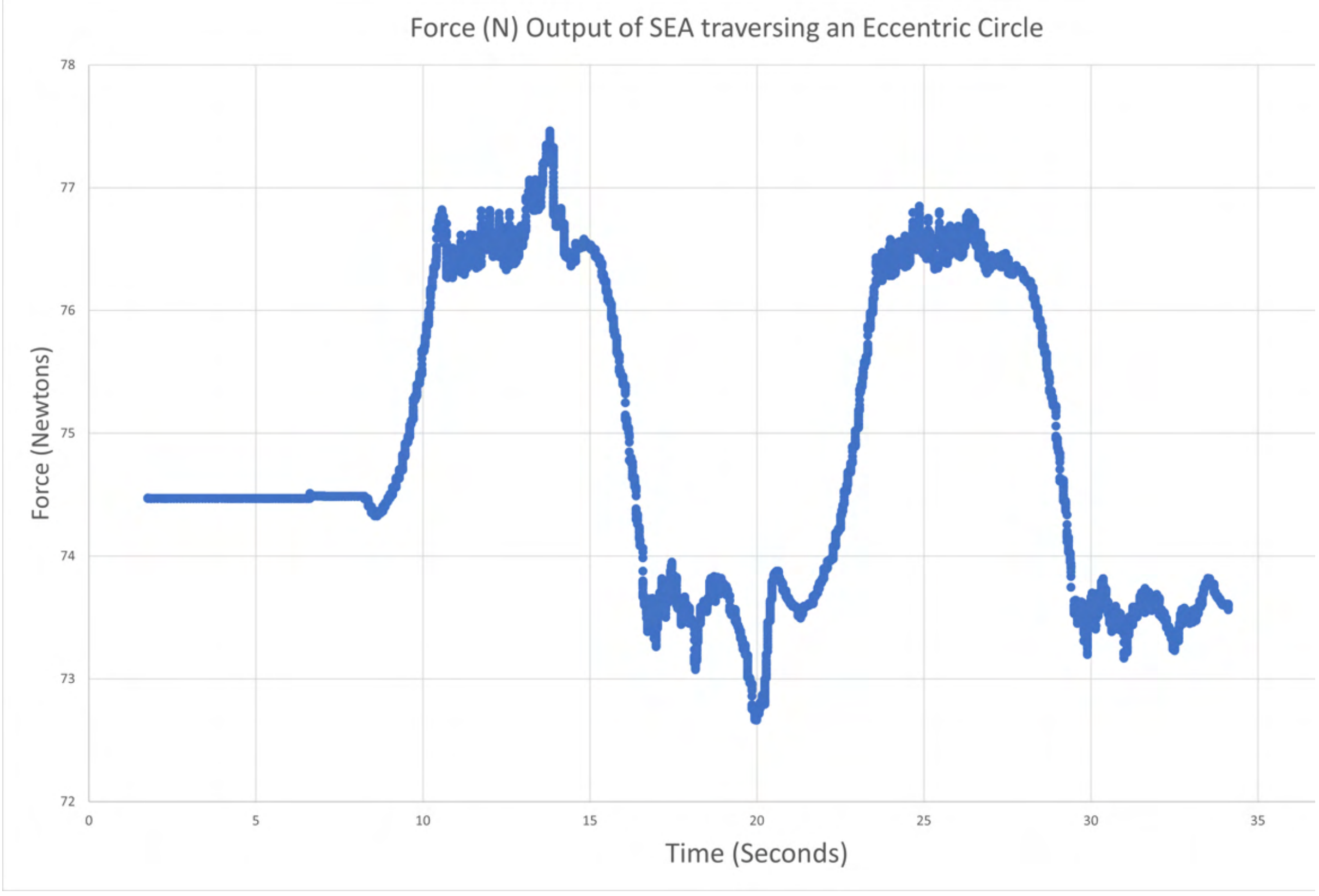
A selection of the tests and results from evaluation:

In these tests, AFP machine was made to apply 75N of force as a disk was rotated under the roller. The disks represent shapes the machine would have to make when building a socket. As a control object, one disk was a circle with an axle that was 6.3 mm off-center, making it an eccentric disk. Two additional disks were made from cross sections of a socket recently designed in Biomech. With the eccentric disk spinning with an average surface speed of 27mm/s2 the standard deviation of the force applied by the SEA was 1.2N. As the surface height gradually increased the Y axis was slow to react. Eventually, as the height further increased the Y axis began to move and compensate for the new height. The behavior was identical as the surface disk peaked and the surface moved downwards. This is due to PID loop tuning. With a constant surface height, the actuator would approach the desired set-point but would often fall short. The system has sufficient power to fully compress the spring, as happened many times during tuning. PID loops can be used to quickly produce usable performance from an actuator but are difficult to optimally tune. This result shows the system is ready and capable to further develop fiber placement, but warrants testing of a more capable control method. The force output on the socket cross sections were constant within a standard deviation of 1.17N and 1.01N respectively.

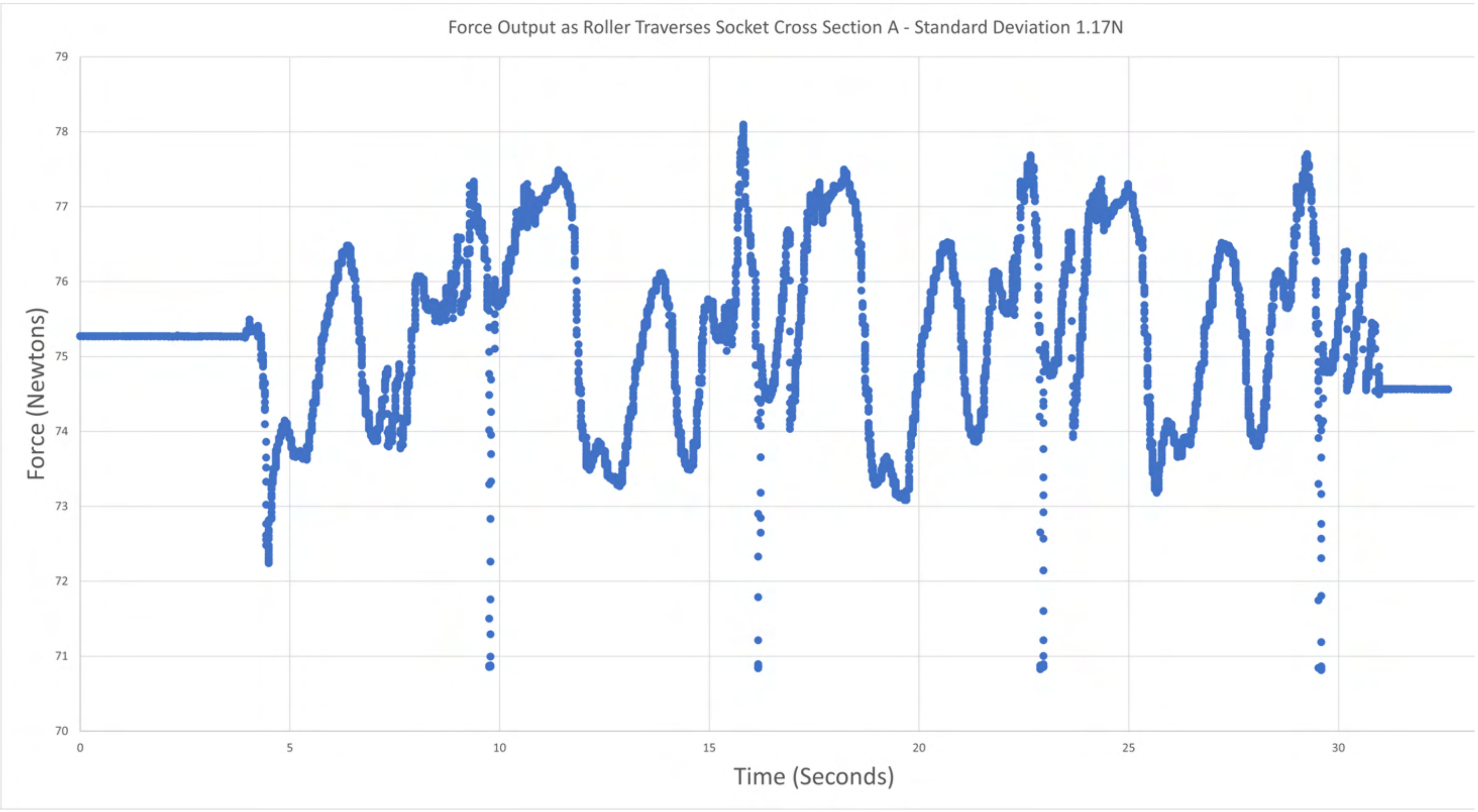








Force (N) Output of SEA traversing an Eccentric Circle

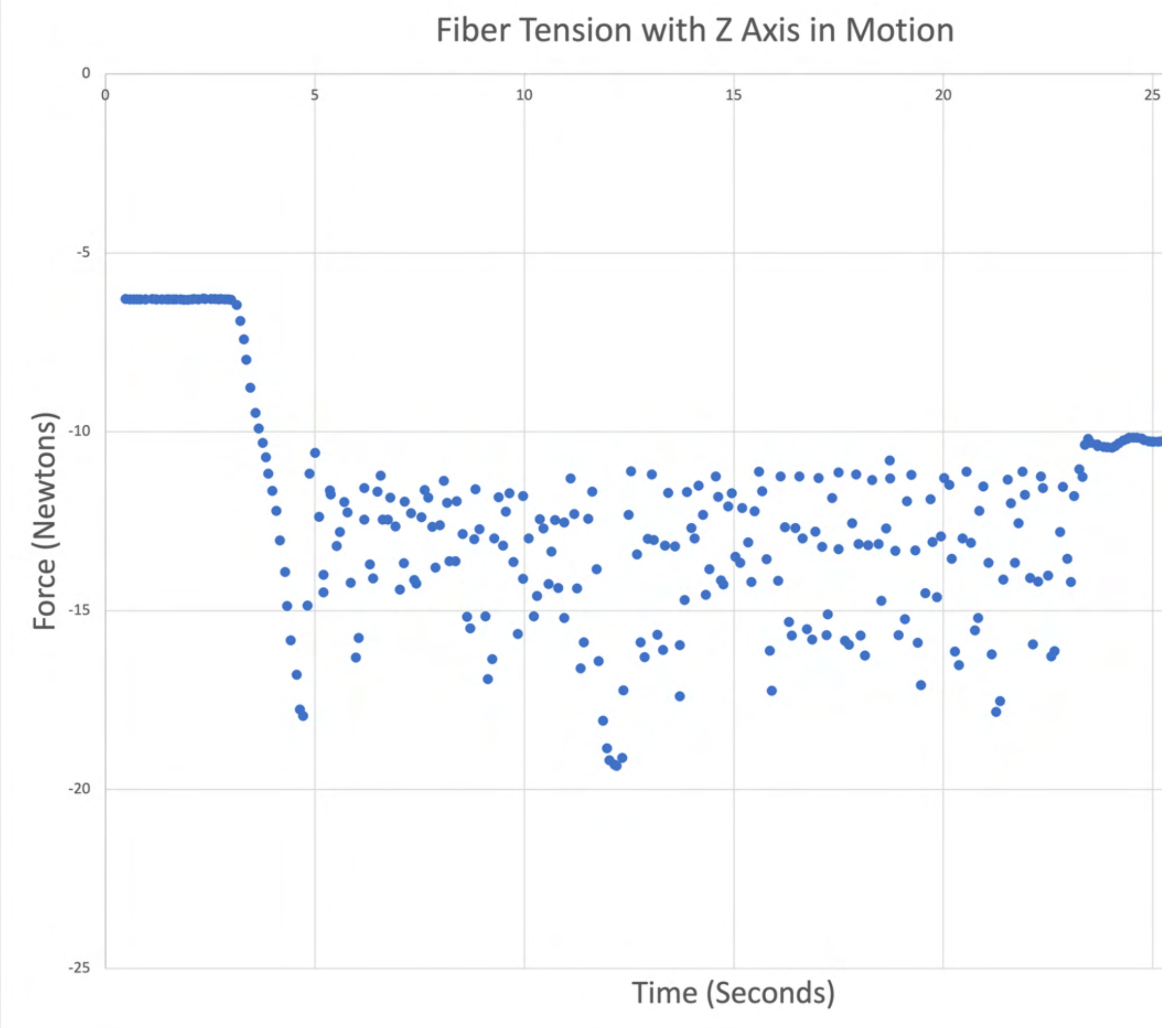


Force Output as Roller Traverses Socket Cross Section A - Standard Deviation 1.17N

Fiber DOF Runout

The Shaft-to-spline adaptor part has noticeable runout, the axis does not perfectly rotate around itself. It is difficult to measure the runout directly at the compaction roller. Therefore, the runout was measured with the dial indicator on the circular surface at the top of the roller fork. The runout was measured at 500 tick increments. The maximum runout was at 108°of -0.48mm. Using Abbe Error, that principle that angular error is magnified over increasing distance where $E = h * sin(\theta)$, the error at the end effector was estimated to be -0.92mm

To measure the fiber tension during placement, the end of the fiber tow was connected to the Futek LSB302 load cell. The tension motor was turned on and the system was moved across the Z axis simulating fiber placement. The results are shown in Figure 8- 5A. The graph shows that the back-driven motor can achieve 10N of tension, however the force was not constant. This was also visually apparent as the fiber seemed to un- spool at an inconsistent rate. Figure 8-5B shows the time in milliseconds that it took for the encoder value to change as the fiber was un-spooled. This is a measurement of velocity, but without the unit conversions. This graph is useful as it shows that the non-constant tension is a result of the motor and not from another part of the assembly. It also indicates that because the change in velocity is measurable by the micro-controller, the issue could be fixed with software. Currently, the tension motor is given a constant voltage, but this suggests that the performance could be improved by a control loop that varies the motor voltage. Figure 8-5C shows the electrical current drawn by the tension motor during operation. This did not show a discernible pattern, potentially, further testing with a higher sampling rate may provide more useful information.



Fiber Tension with Z Axis in Motion

SRSA Project Overview 2017-2019: Biomechatronics’ Patient Scanner

Project: Designed and implemented a patient Scanner and Indenter to capture the time-varying 3D shape and mechanical properties of a residual limb.

Project Impact: This work aims to replace the current manual socket design process that is expensive and often leads to poor fitting sockets. Painful sockets can result in negative health outcomes: weight gain, depression, even further amputation.

Research Impact:

Scanner performed data collection for n=18 NIH funded clinical trial.

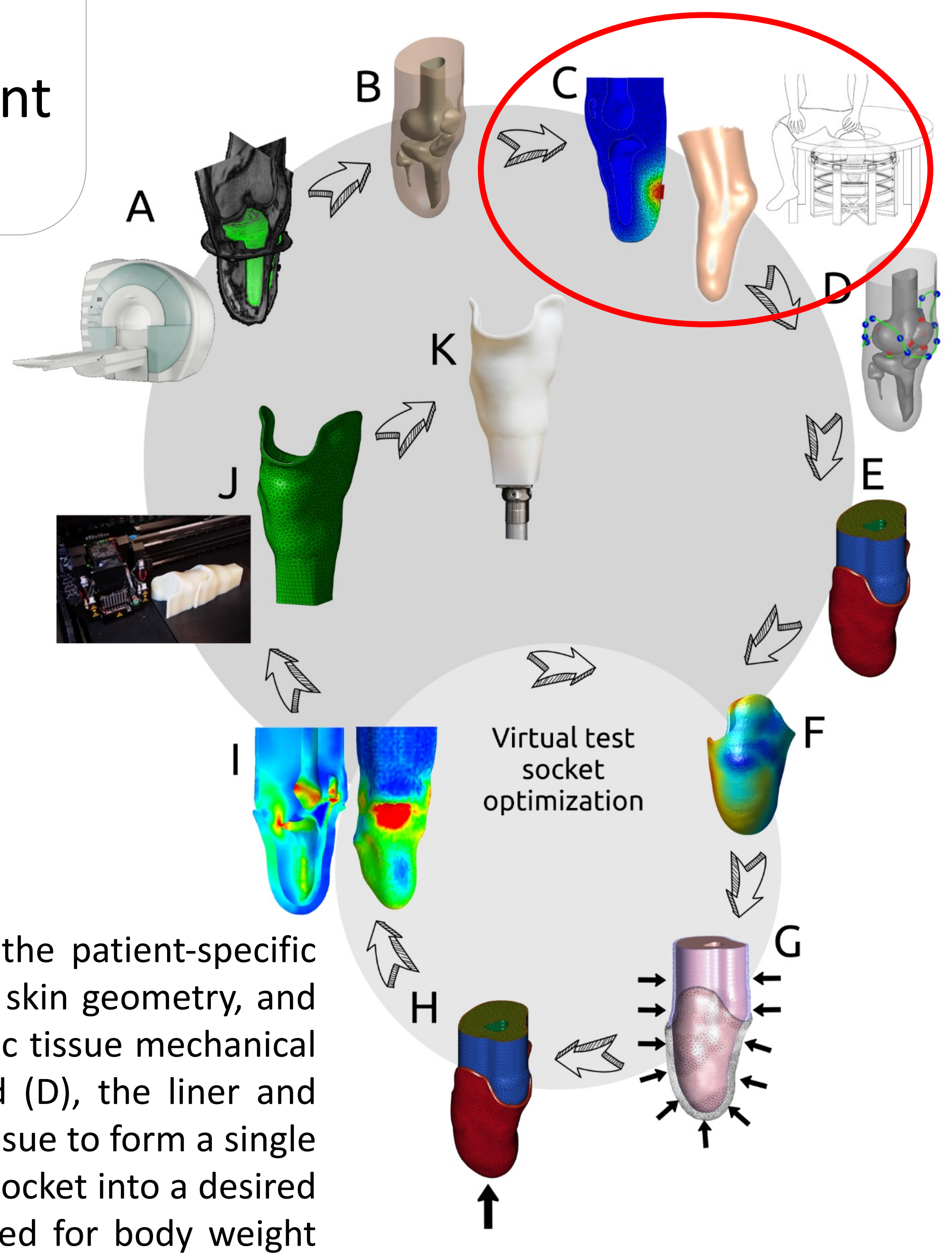
Data from this scanner is included in two peer reviewed publications (cited on next page)

Data assisted three research scientists in advancing their careers to professorship.

Two additional Master’s students depended scanner data for thesis work.

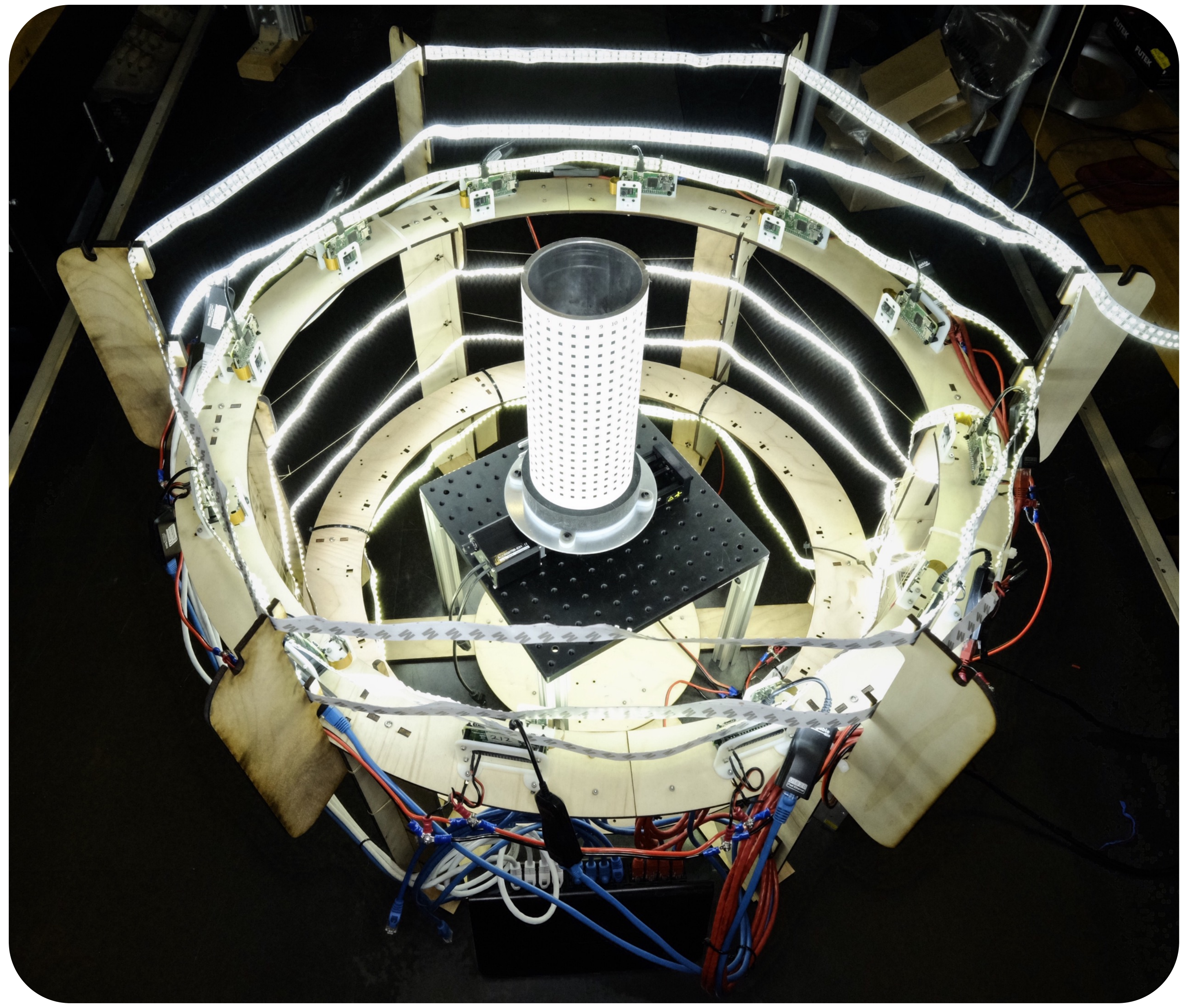
The scanner is included in Biomech’s Socket Design Patent (Cited next page)

Project Role: The work for the clinical trial was done by a small group of researchers. I was responsible for the entire data acquisition system. I was supervised by Research Scientists and developed the system to meet their data needs. Throughout the project I mentored undergraduate students working for Biomech.



Overview of the data-driven computational design framework. By segmenting MRI data (A), the patient-specific geometry is obtained (B). Digital Image Correlation (DIC) is employed to obtain more accurate skin geometry, and indentation tests and inverse FEA informed by DIC can be used to determine the patient-specific tissue mechanical properties (C). Using anatomical landmarks the socket cut-lines can be automatically created (D), the liner and socket source geometries can be offset from the skin surface and can be meshed with the soft tissue to form a single FEA model (E), spatially varying fitting pressures is defined (F), allowing for the morphing of the socket into a desired shape, while also pre-loading the tissue due to donning (G), the designs can now be evaluated for body weight loading (H), enabling skin surface pressure and internal strain analysis (I). The process F-I can be iteratively repeated and optimal designs can be exported for 3D printing based manufacturing (J) of final socket (K). Figure and description: Kevin Moerman, Dana Solav

First Prototype of Scanner System

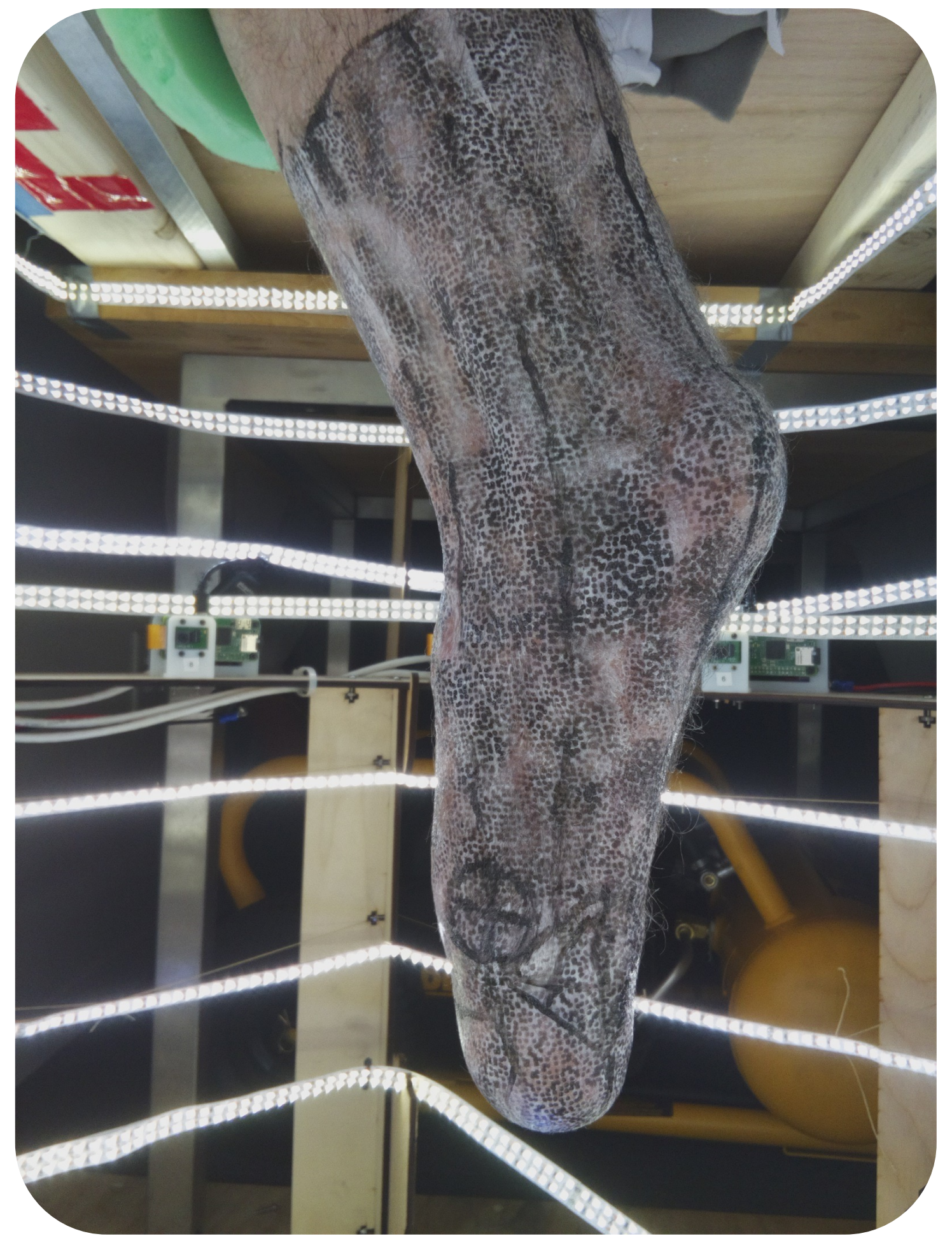


I built this first prototype from discarded materials during my first month in Biomech. It was iterated upon for a year as our research team figured trial protocol.

Camera Calibration Object

The calibration object allows for simultaneous stereo calibration for each camera. It features 700 black rectangular planar faces on a white background. The 3D coordinates of the centroids of black dots used to obtain the stereo triangulation parameters

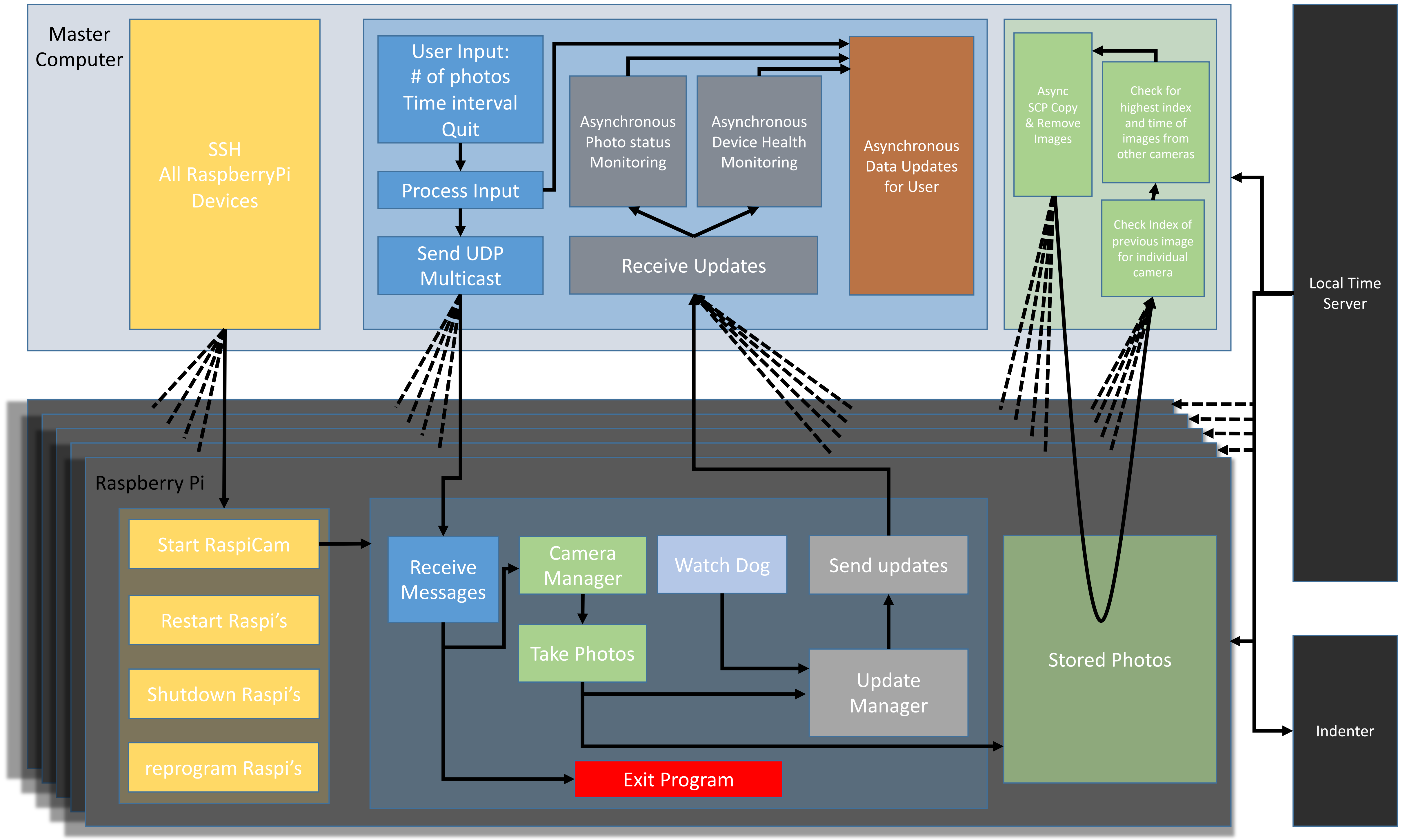
Photo Credit: Jerry Jaeger



Speckled Residuum during scanning. Additional markings noting sensitive regions and anatomical locations

3D reconstructions of residuum. Figure Credit: Dana Solav

The designed socket model can be 3D printed using rigid Vero material, and get the rigid socket which can be connected to the foot/ankle system



High Level Scanner System Software Overview

I had to account for the four following factors when implementing the scanner’s software architecture. First, there are a lot of cameras, and the number of cameras continues to increase as our research needs progress, therefore the cameras must be independent units and the system be scaleable. Second, the devices are unreliable and prone to crashing, we can’t spend an hour with a test subject only to find out the next day that we failed to collect data. Third, the cameras need to capture images simultaneously, however they are not running an RTOS and therefore operate asynchronously. The cameras need to function in parallel but cannot block other devices from operation. Finally, due to the number of cameras, and time sensitivity of every operation, every task must be automated.

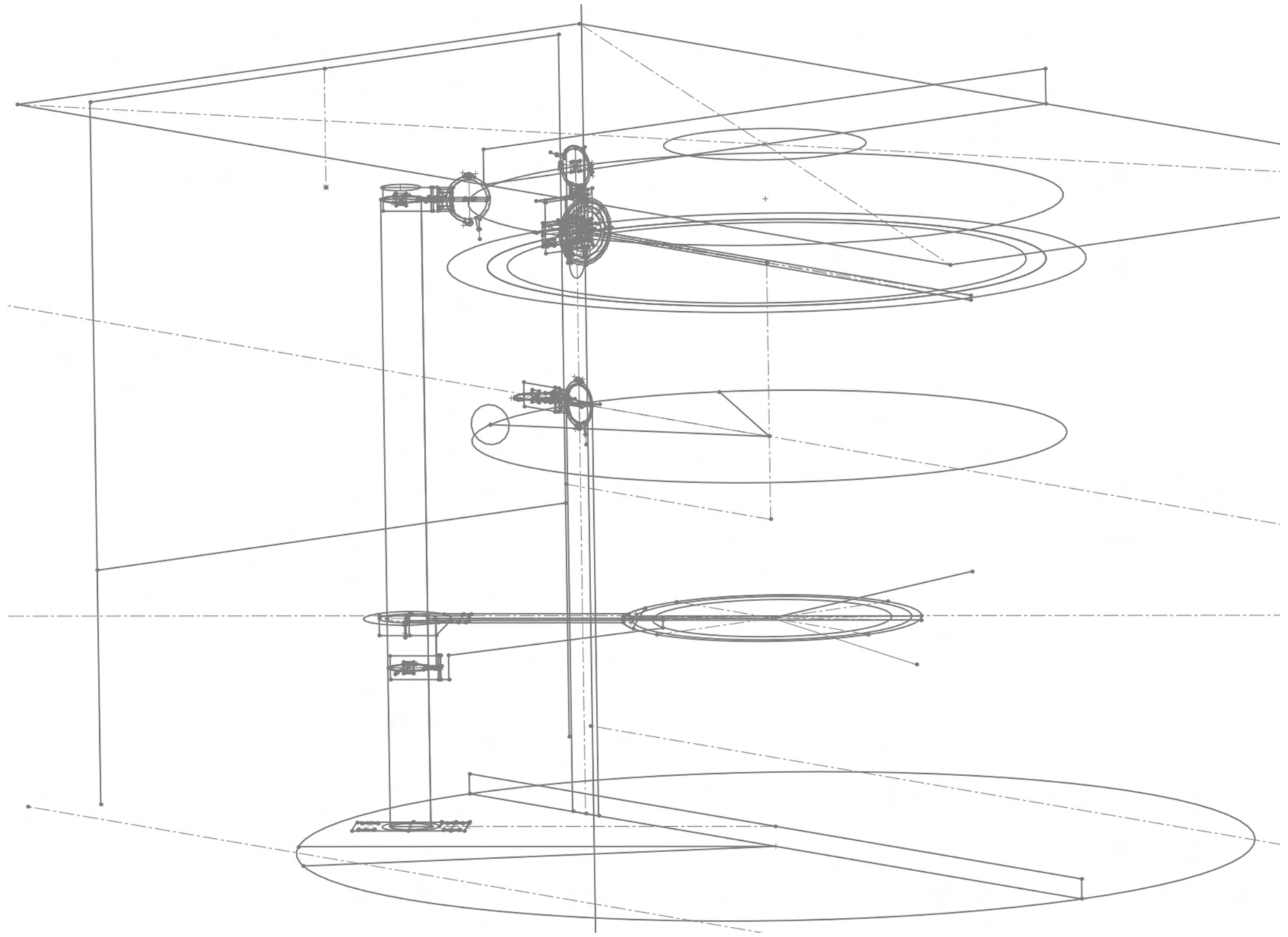
Biomechatronics Patient Scanner: Scanner Hardware V2

Hardware Revision Goals:
Upgrade the patient scanner based on learnings from first prototype.

Design the system to be a robust and upgradable platform that can support future subject measurement projects.

Gain experience working with outside manufacturers and vendors.

Scanner Master Model Sketch

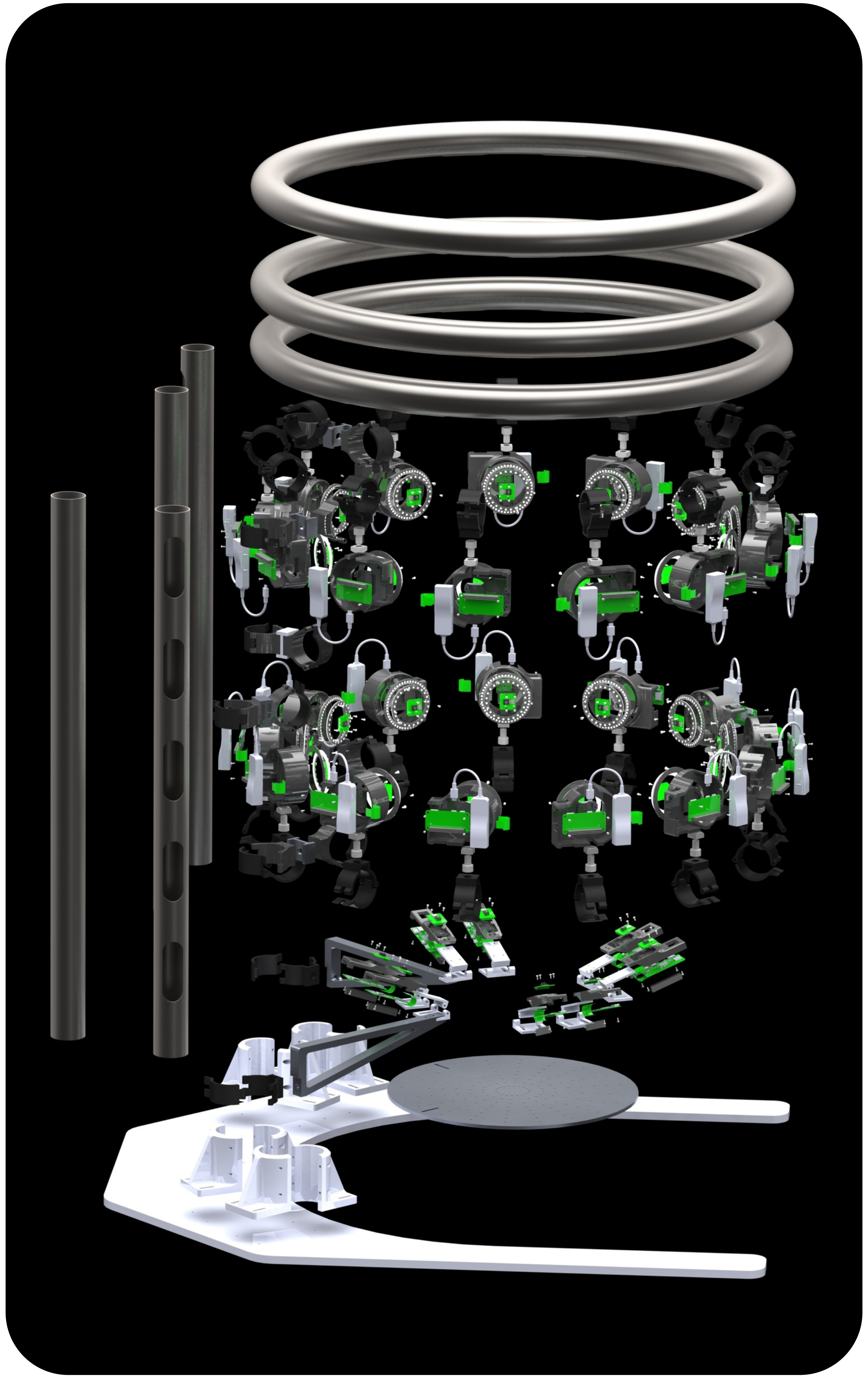


Publications supported by the two scanners:

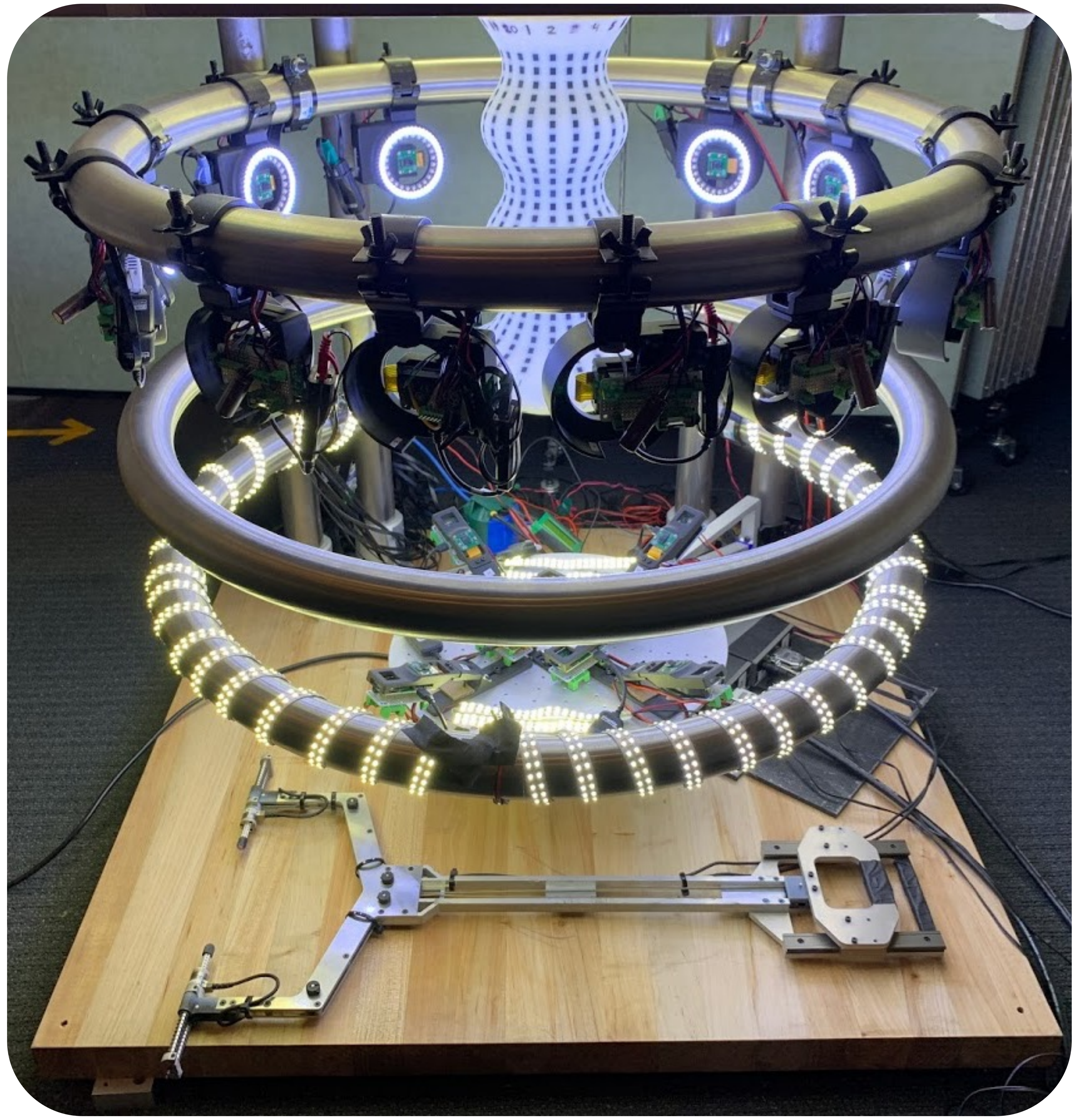
D. Solav, K. M. Moerman, A. M. Jaeger, K. Genovese and H. M. Herr, "MultiDIC: An Open-Source Toolbox for Multi-View 3D Digital Image Correlation," in *IEEE Access*, vol. 6, pp. 30520-30535, 2018, doi: 10.1109/ACCESS.2018.2843725.

D. Solav, K. M. Moerman, A. M. Jaeger and H. M. Herr, "A Framework for Measuring the Time-Varying Shape and Full-Field Deformation of Residual Limbs Using 3-D Digital Image Correlation," in *IEEE Transactions on Biomedical Engineering*, vol. 66, no. 10, pp. 2740-2752, Oct. 2019, doi: 10.1109/TBME.2019.2895283.

Scanner Assembly Exploded



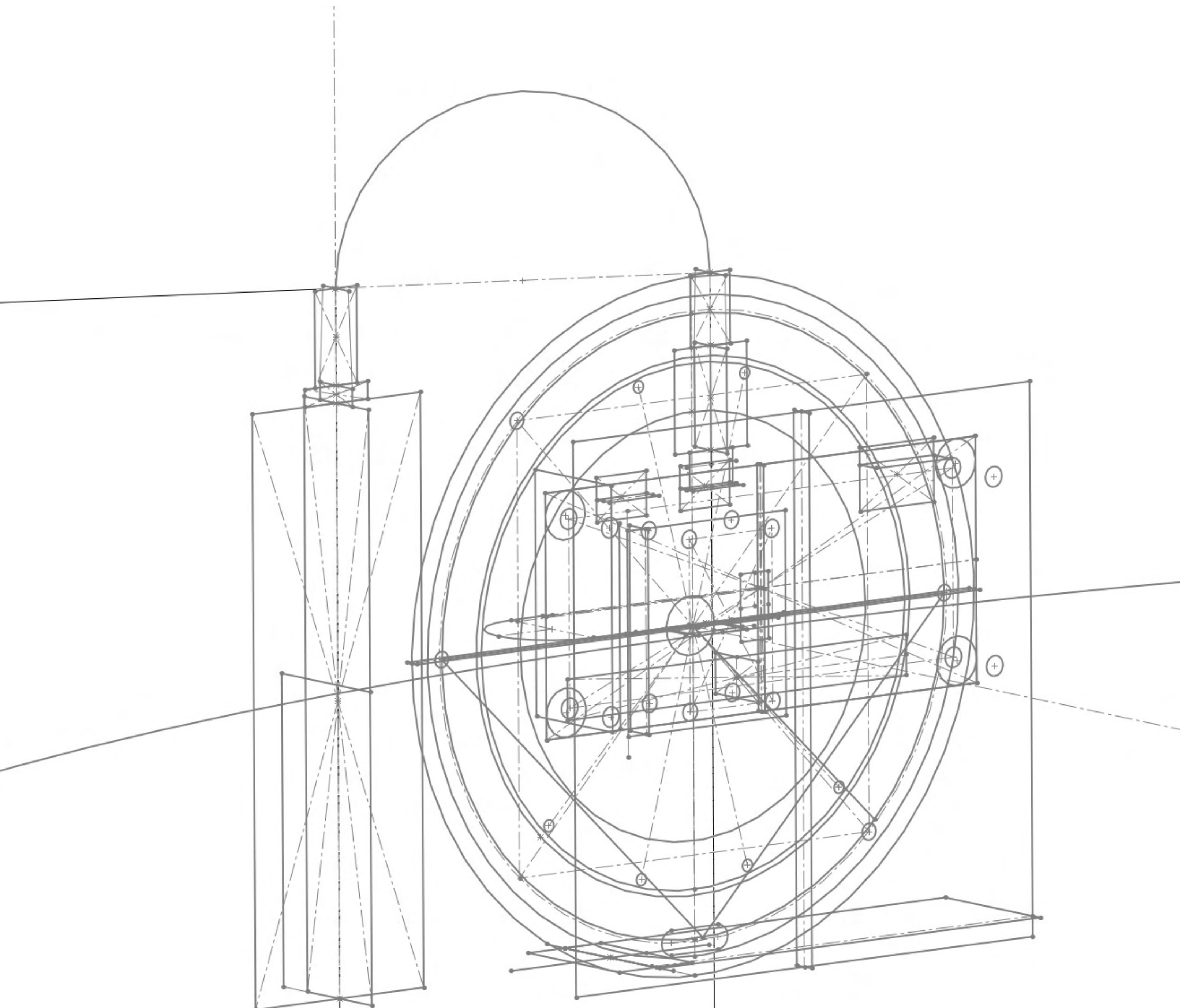
Scanner System



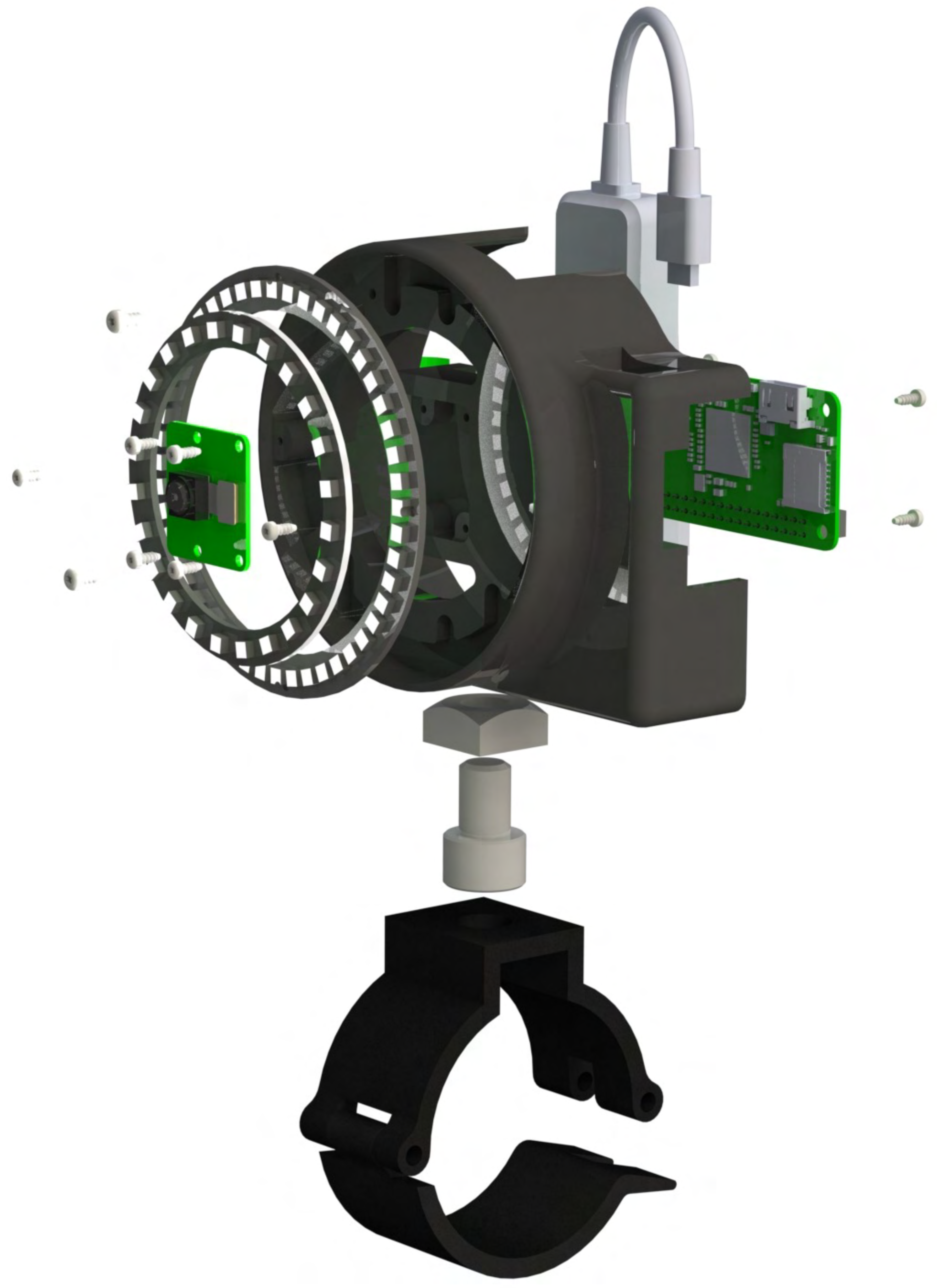
Design Considerations
- Scanner frame and components designed to be rigid, and prevent camera calibration issues from accidental contact
- Slotted Rings and legs allow for cleaner internal wiring
- Design allows greater adjustability for repositioning camera location, height, and orientation
- Better wiring, and position adjustment also accommodates adding extra cameras when necessary
- Dual camera rings expand capture volume
- Has large opening and support railing for Indenter
- Components are easily accessible
- Attractive design

Biomechatronics Patient Scanner:

Camera Assembly V2

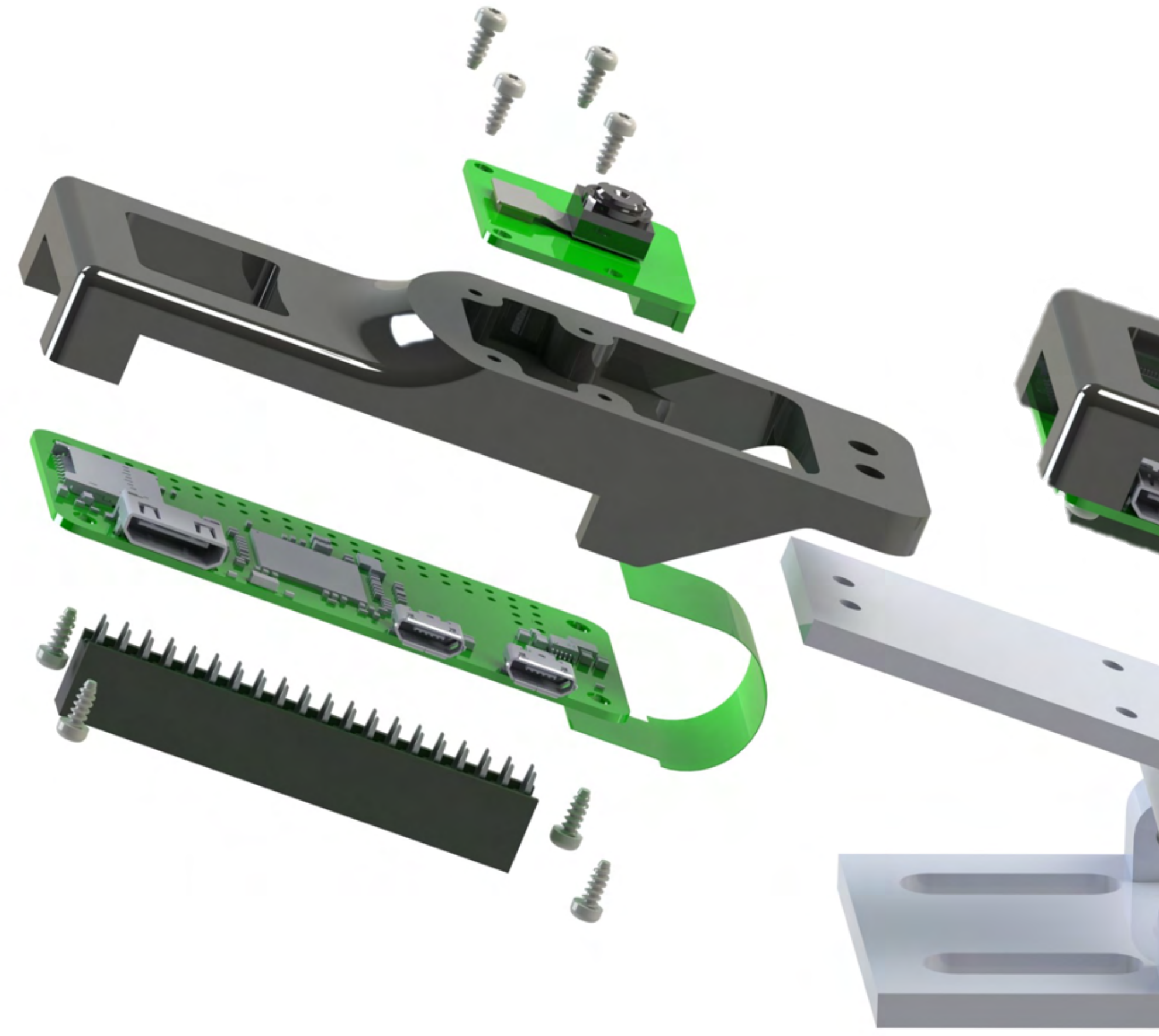


Camera Master Model

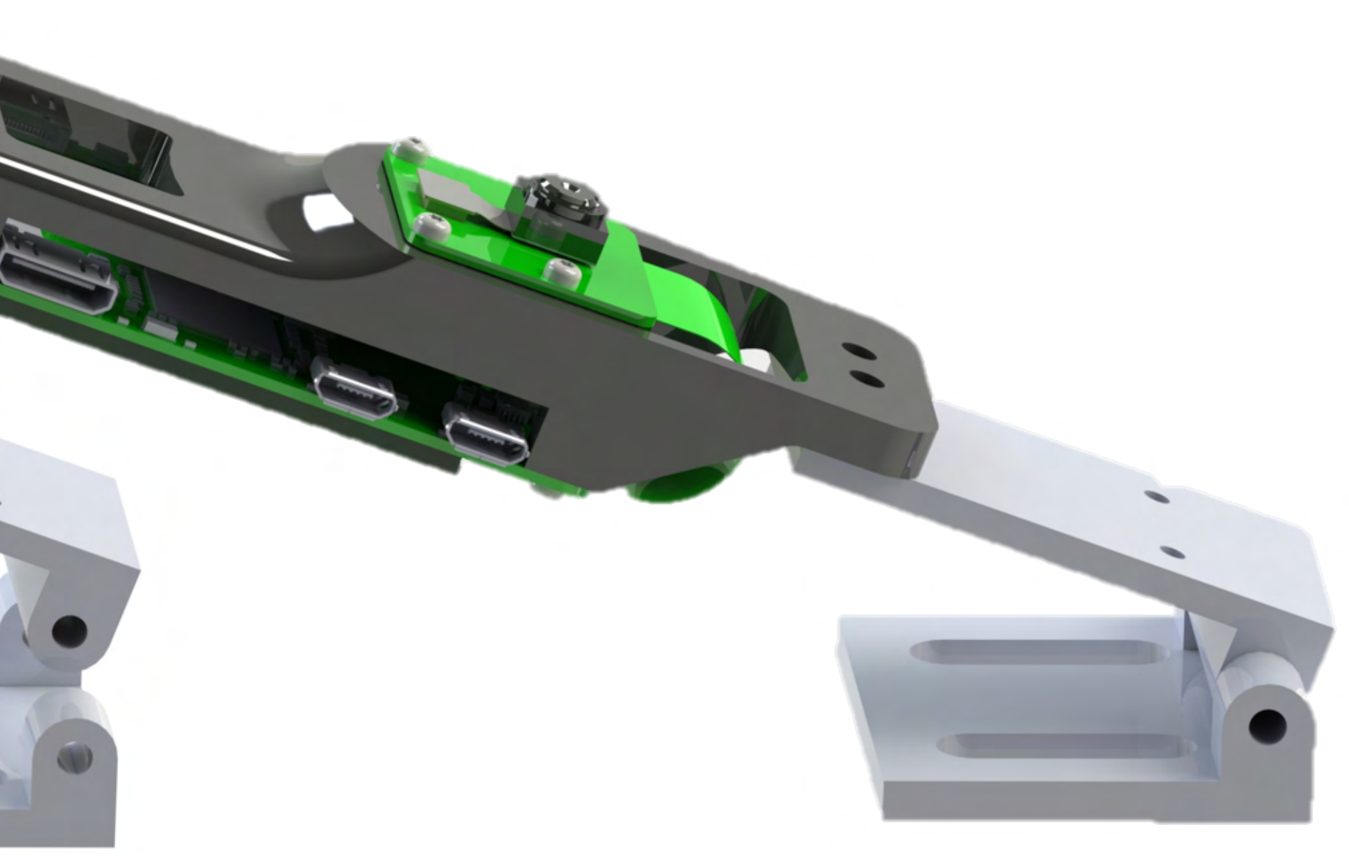


Exploded Camera Assembly

Camera Master Model



Exploded Bottom Camera



Bottom Camera

Camera Design Considerations

- The new scanner was intended to have 34 cameras
- The unibody case is designed so all parts only require screws to be attached
- Manufactured with vacuum casting process
- No standoffs, spacers, nuts, washers
- Self tap screws reduce manufacturing cost
- Reduced parts simplify assembly, and reduces costs
- Outer LED ring lights up camera field of view, and reduces clutter over previous light
- Inner ring of RGBW lights provide test subject and clinician feedback
    - Scanner currently requires operator to sit behind screen separate from test subject, a light feedback interface was intended to remove the separation

Camera Case Front

Photo Credit: Jerry Jaeger

Camera Case Front

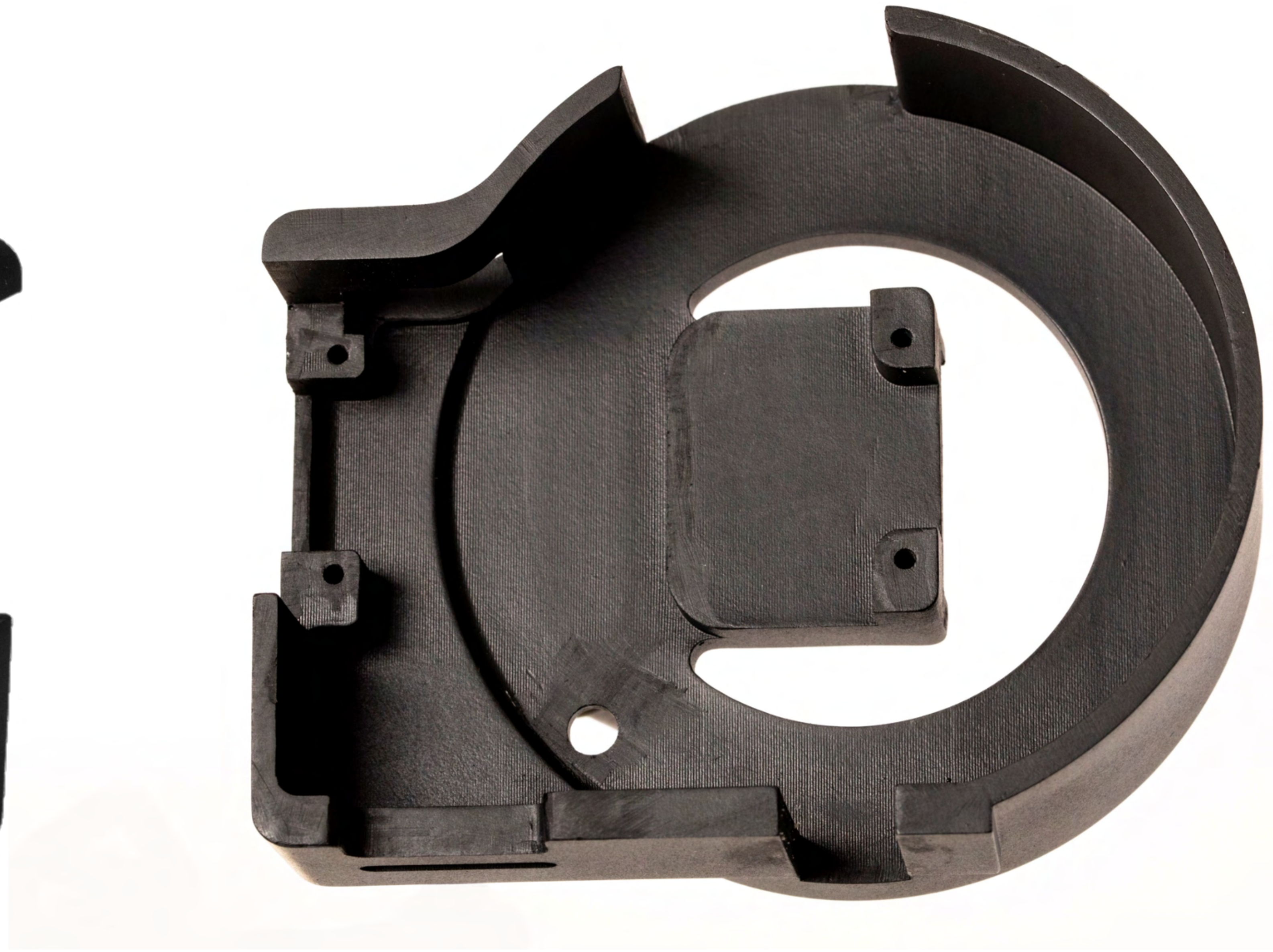


Photo Credit: Jerry Jaeger

Unibody Case Front

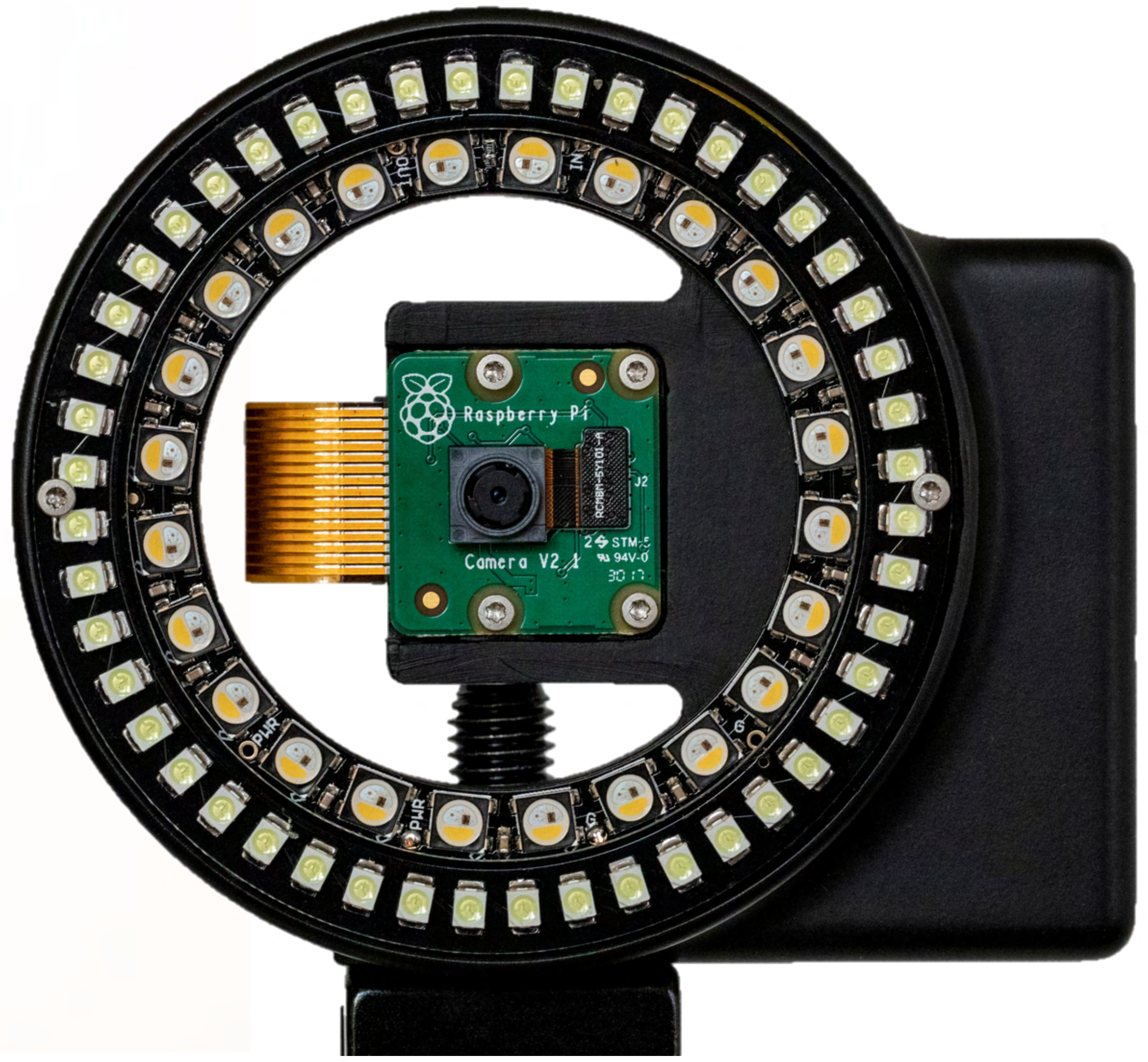


Photo Credit: Jerry Jaeger

Biomechatronics Patient Scanner:
Indenter

Project Goals:

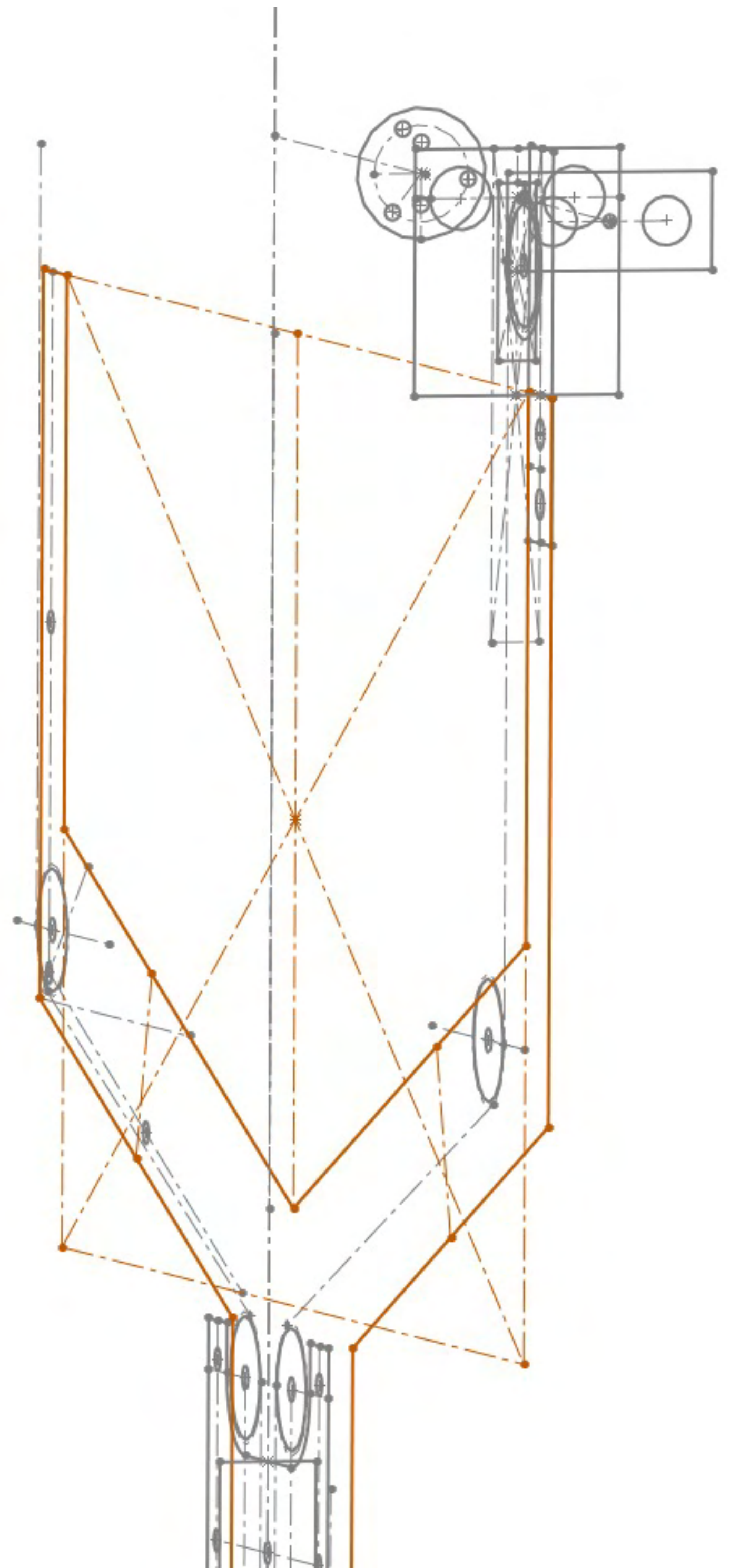
Tool used with patient scanner to determine residual limb soft tissue properties.
Deform tissue and measure force in 6 DOFs

Avoid:

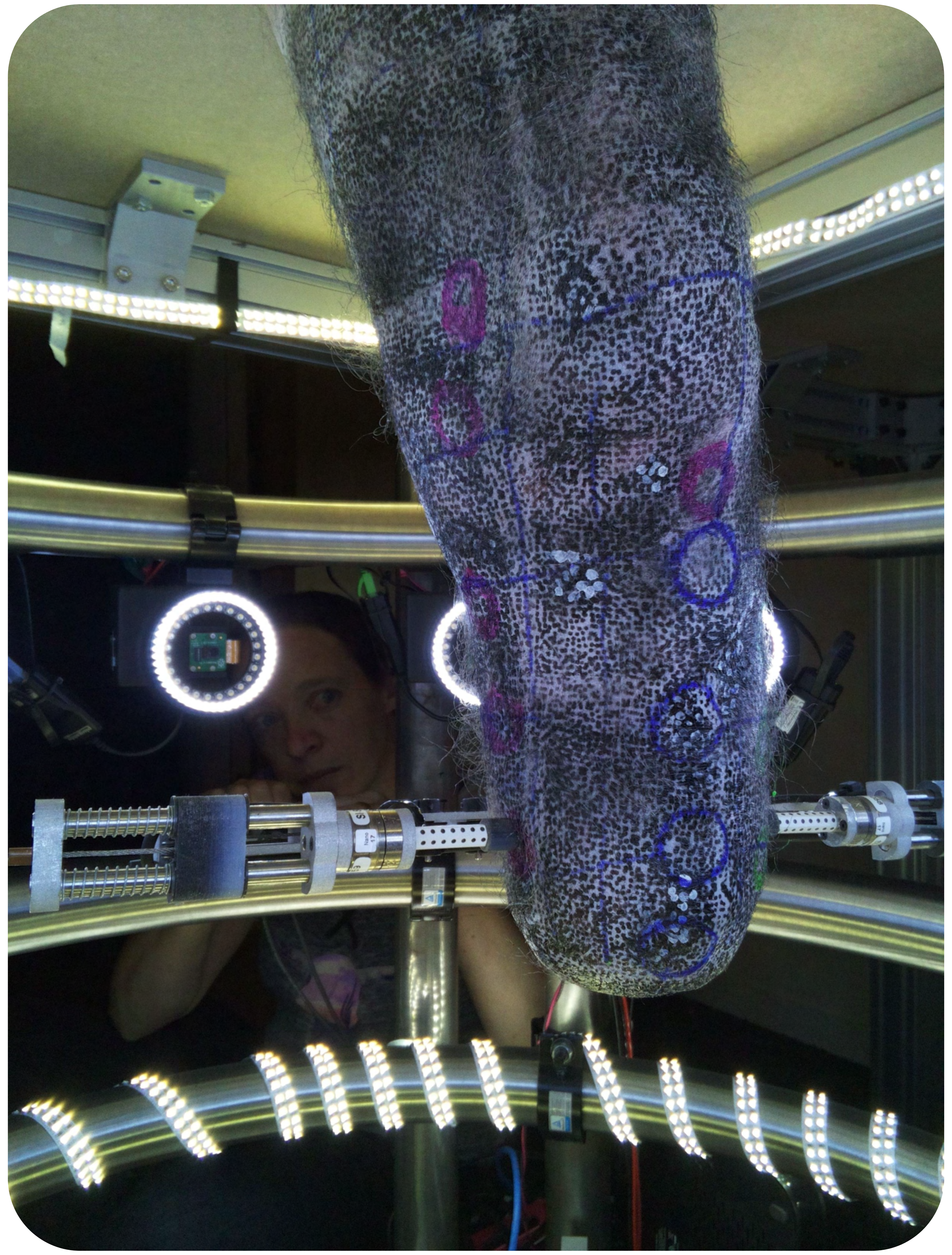
- Hurting the test subject
- Blocking the cameras
- Moving the patient's leg

Design considerations:

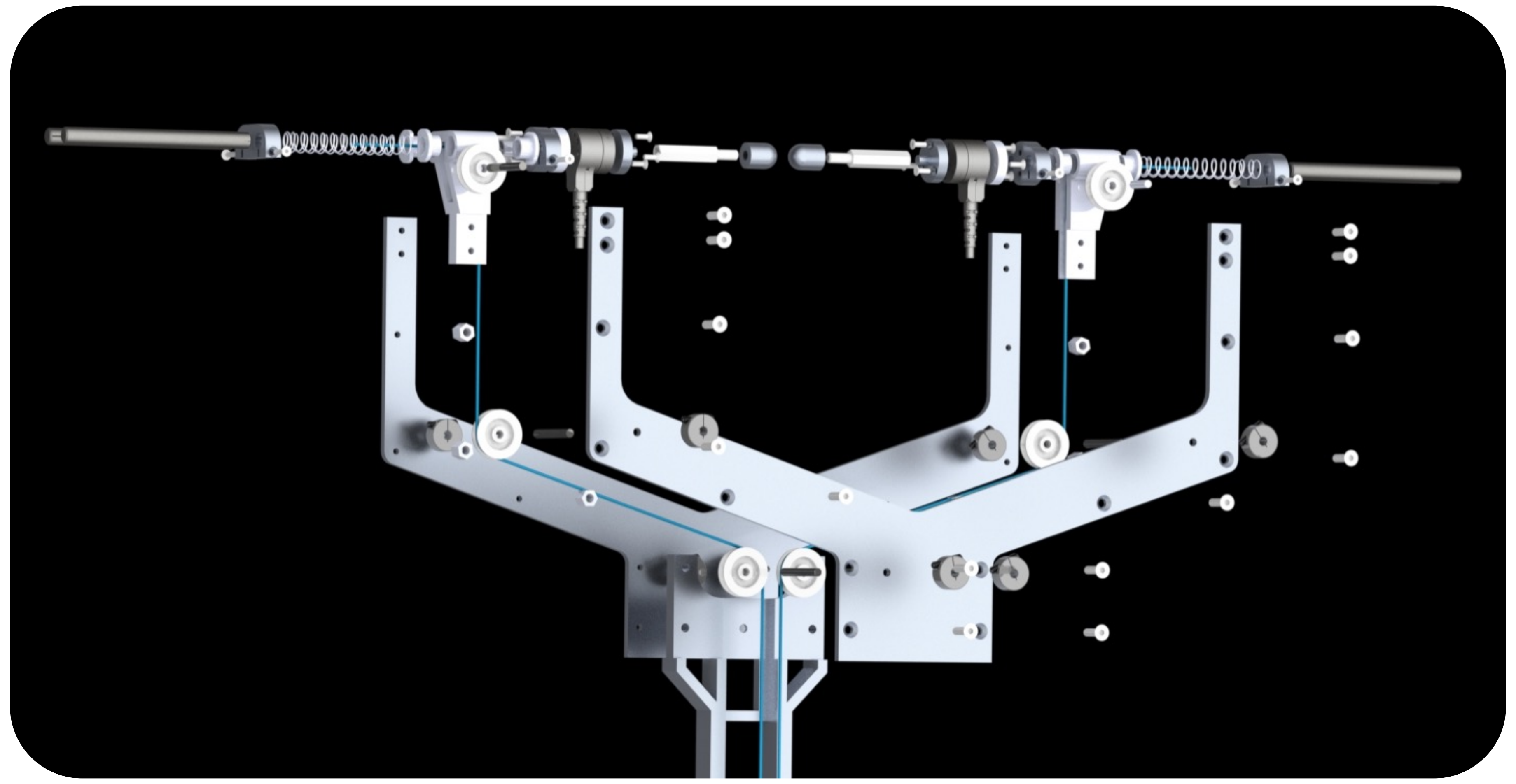
Parts design influenced by available manufacturing method capabilities. It was designed so I could easily machine the parts with a combination of the water jet, and manual mill.



Indenter in Use

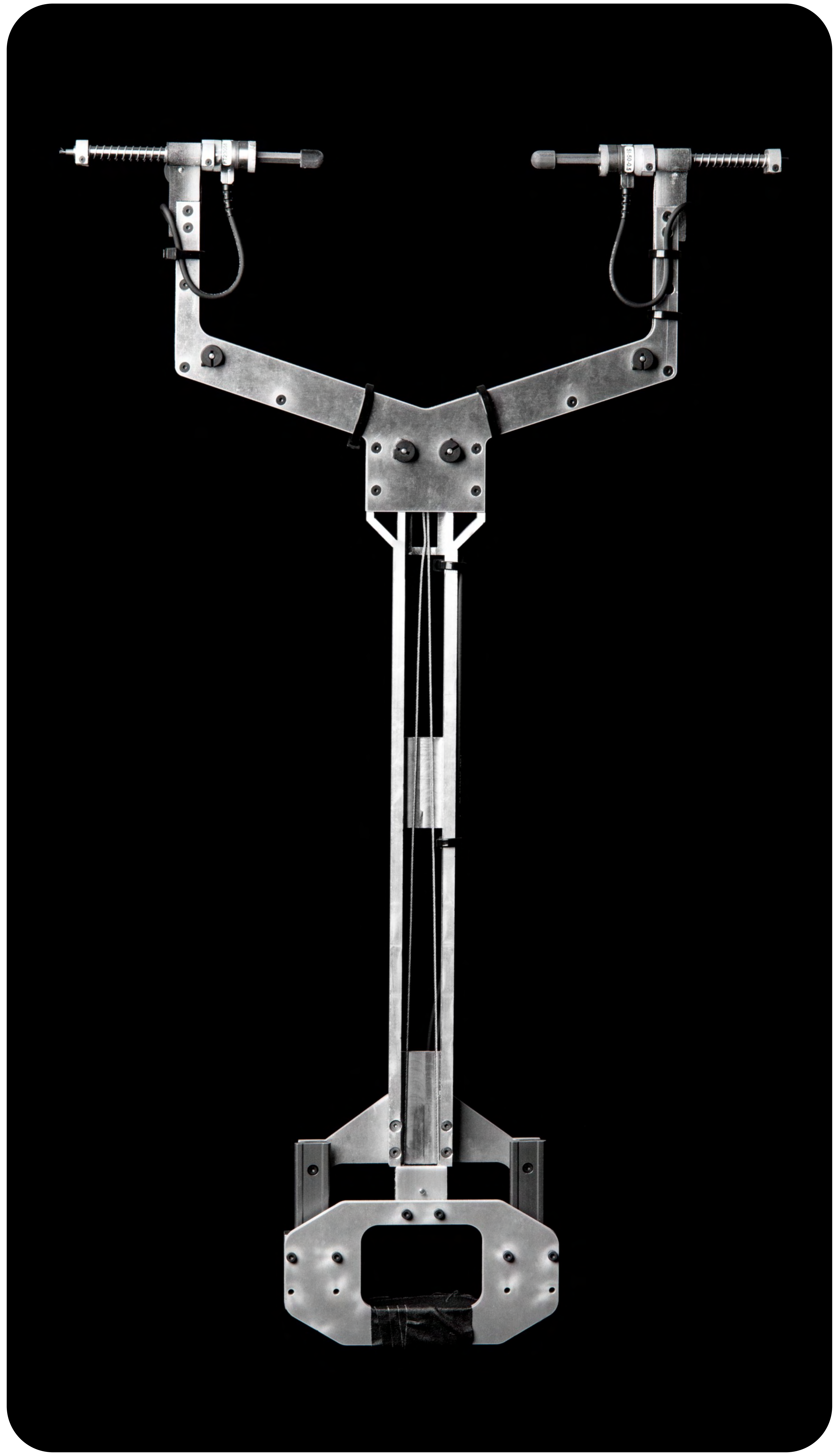


Indenter Exploded



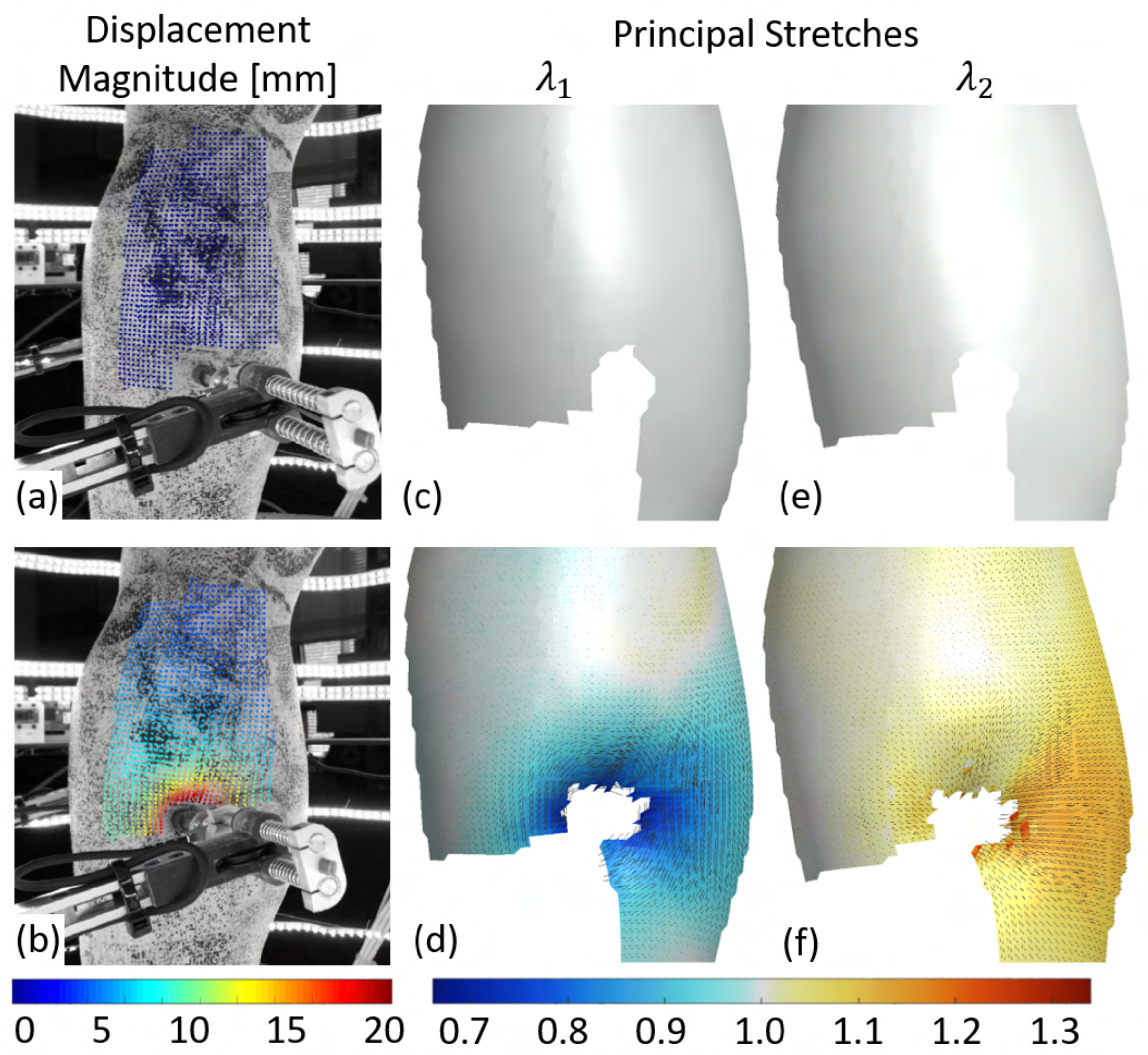
Indenter

Photo Credit: Jerry Jaeger



The data from the indenter and scanner are combined to determine the mechanical properties of the limb's soft tissue. A simulated indenter using the real indenter's measurements presses on simulated soft tissue, defined by best guess Ogden parameters. If the behavior of the simulated soft tissue matches the behavior of the real soft tissue, as measured by the scanner, then the Ogden parameters are correct. If the behavior does not match, the parameters are changed, and the simulation is run again.

Professor Hugh Herr presenting the Indenter at Media Lab Member Meeting Fall 2018



Preliminary testing with the Indenter

Figure Credit: Dana Solav

SRSA Project: Socket Validation

Project Goals:

Compare pressure from the socket on residual limb between the traditional socket and the digitally designed socket.

Compare actual pressure in socket to pressure expected from simulation.

Design Considerations:

A limited development timeline meant focusing on creating best practices for using commonly used, but unreliable pressure sensors.

Easy to use UI as this subject trial was especially stressful. Data collection had to happen without user error.

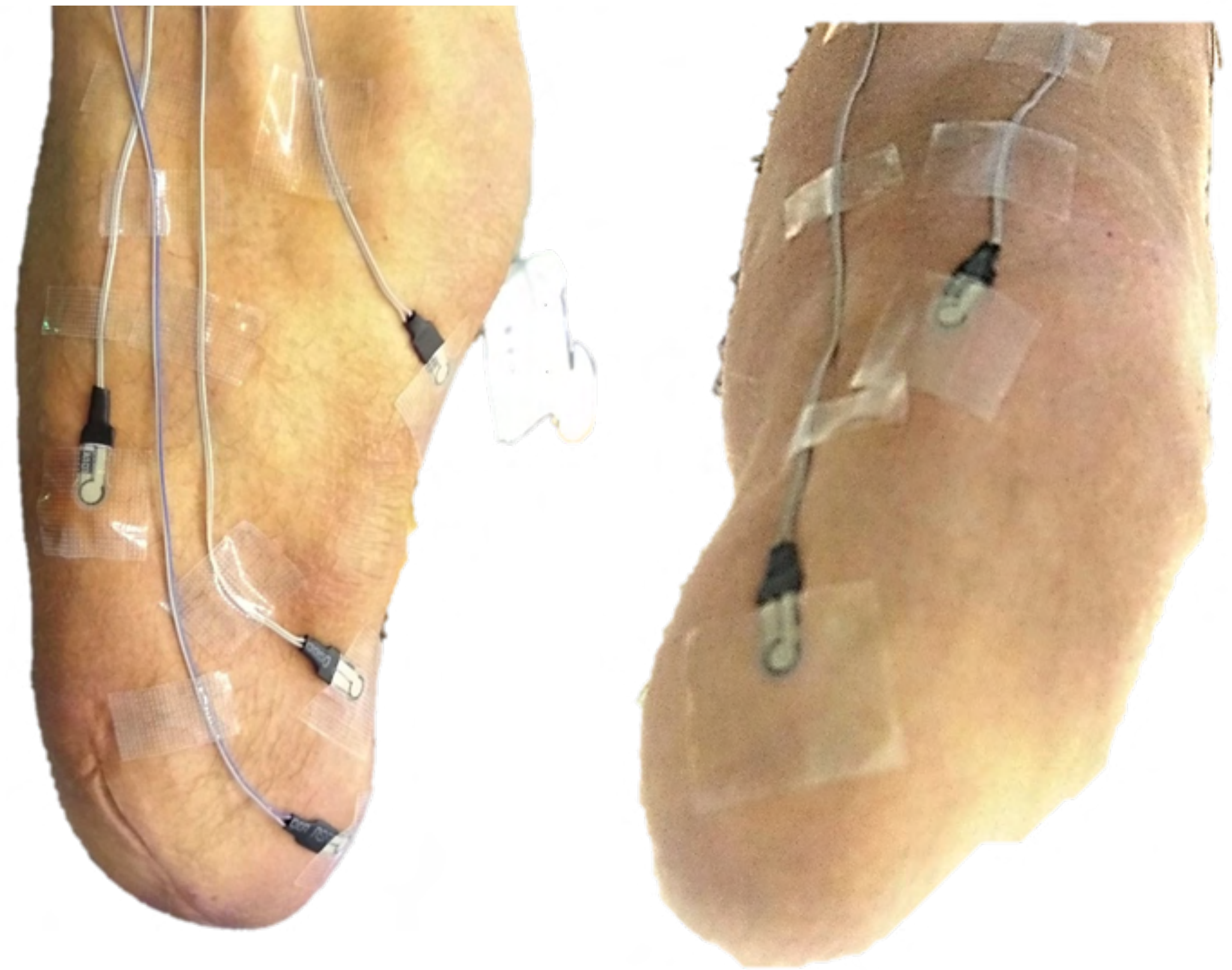
Research Outcome:

Relative pressure comparison between digitally designed socket and traditional socket.

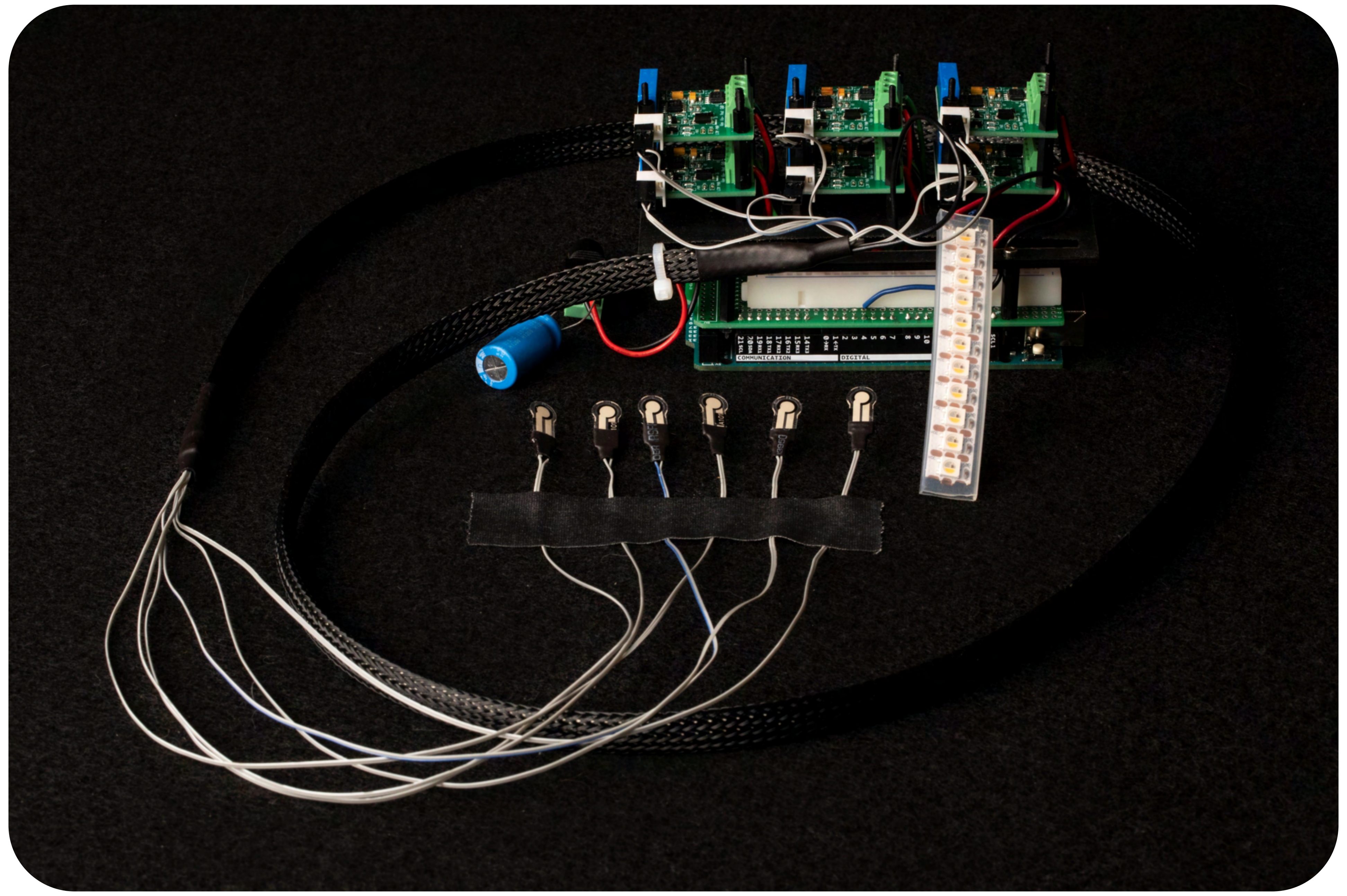
Developed user friendly pressure sensing tool which new new students used to complete NIH trial data collection.

Provided foundational research for incoming Master's student to work on simulated pressure validation.

Sensors Placed at Anatomically Relevant Points



Socket Pressure Validation Sensors



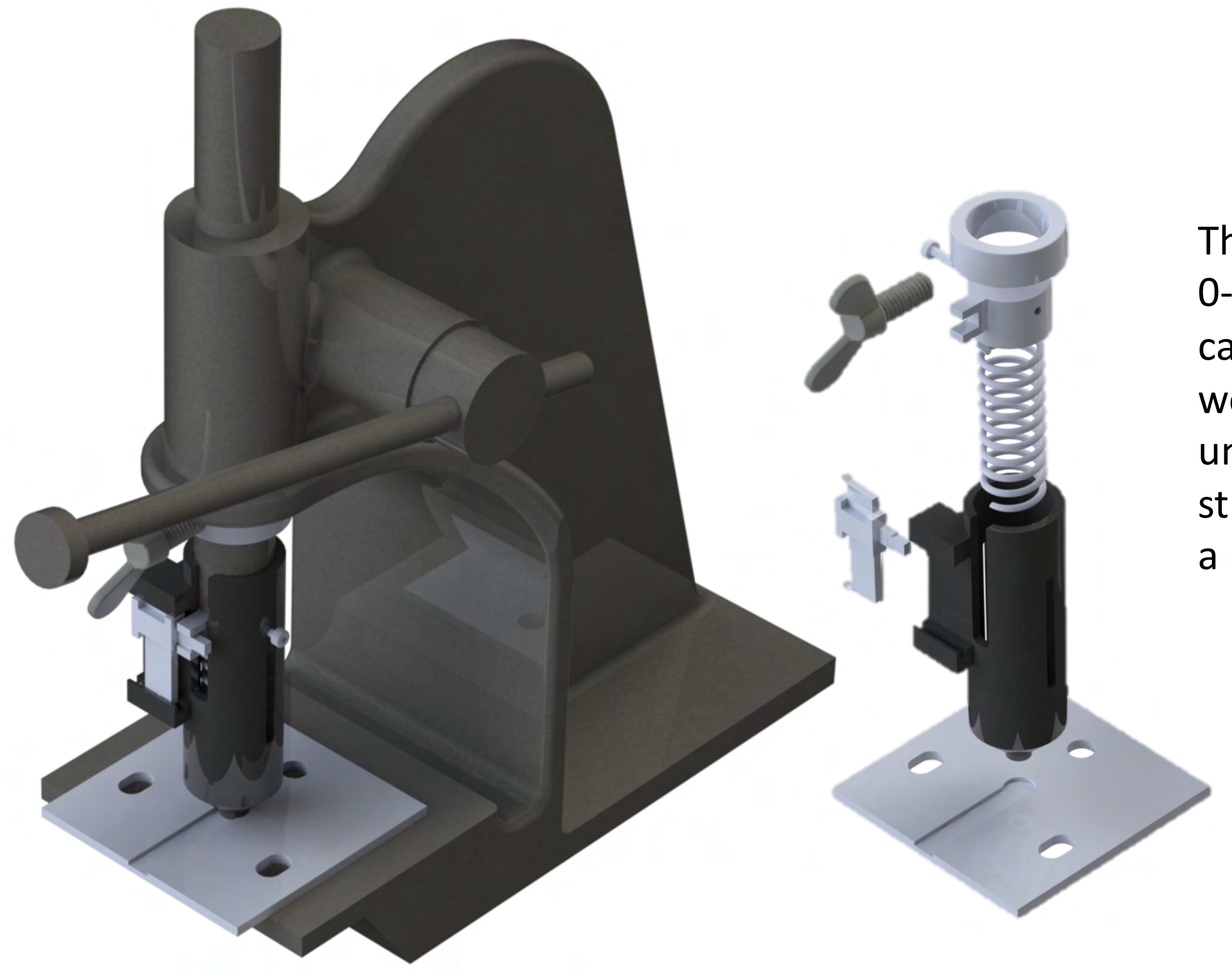
In-socket pressure sensing is unsolved problem. Force sensitive resistors (FSR) are commonly used, but researchers often present the data and ignore their flaws. The sensor behavior changes every time they are used, and gradually drifts while being used. Additionally, the behavior changes when the sensors are bent, as happens when inside of a socket.

After a few different attempts at a calibration method I determined it would be best to drop the ground-truth pressure measurements, and only do a relative and unitless pressure comparison between sockets.

Shortly after the development of this project researchers from University of Washington published their concerns over the use of FSRs for ground truth pressure sensing, an the impracticality of calibration.

Swanson, E. C., Weathersby, E. J., Cagle, J. C., and Sanders, J. E. (July 15, 2019). "Evaluation of Force Sensing Resistors for the Measurement of Interface Pressures in Lower Limb Prosthetics." ASME. *J Biomech Eng*. October 2019; 141(10): 101009. https://doi.org/10.1115/1.4043561

Mentee Project: Sensor Calibration Tool

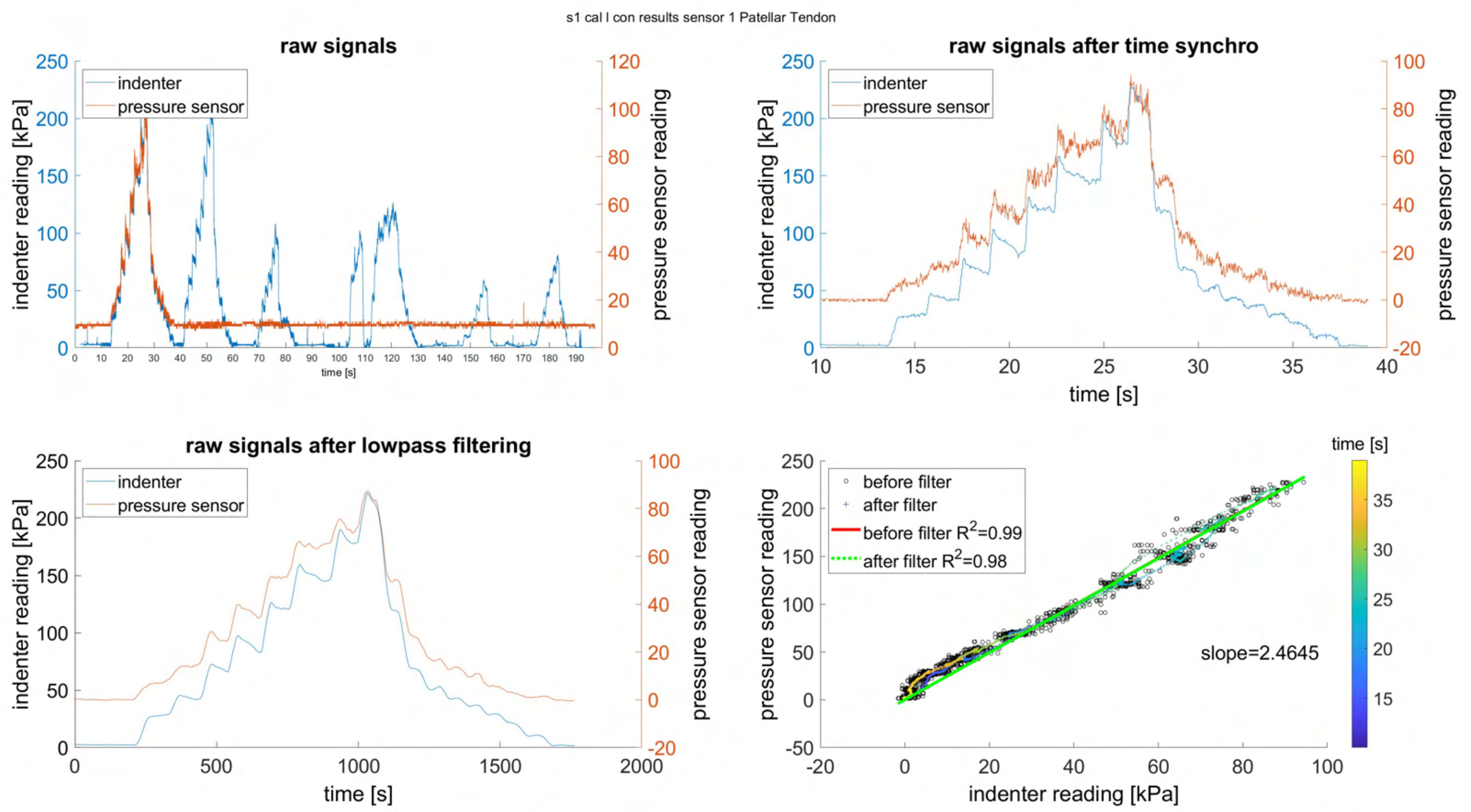


This is a custom force press that can apply and hold a desired load 0-50 N to an FSR. It was one of the tools I used in an attempt to calibrate the sensors. This was designed by an undergraduate working with me in the lab. I have worked project teams as an undergrad and mentored many elementary and high school students on their own projects, however, supervising a student was a new experience.

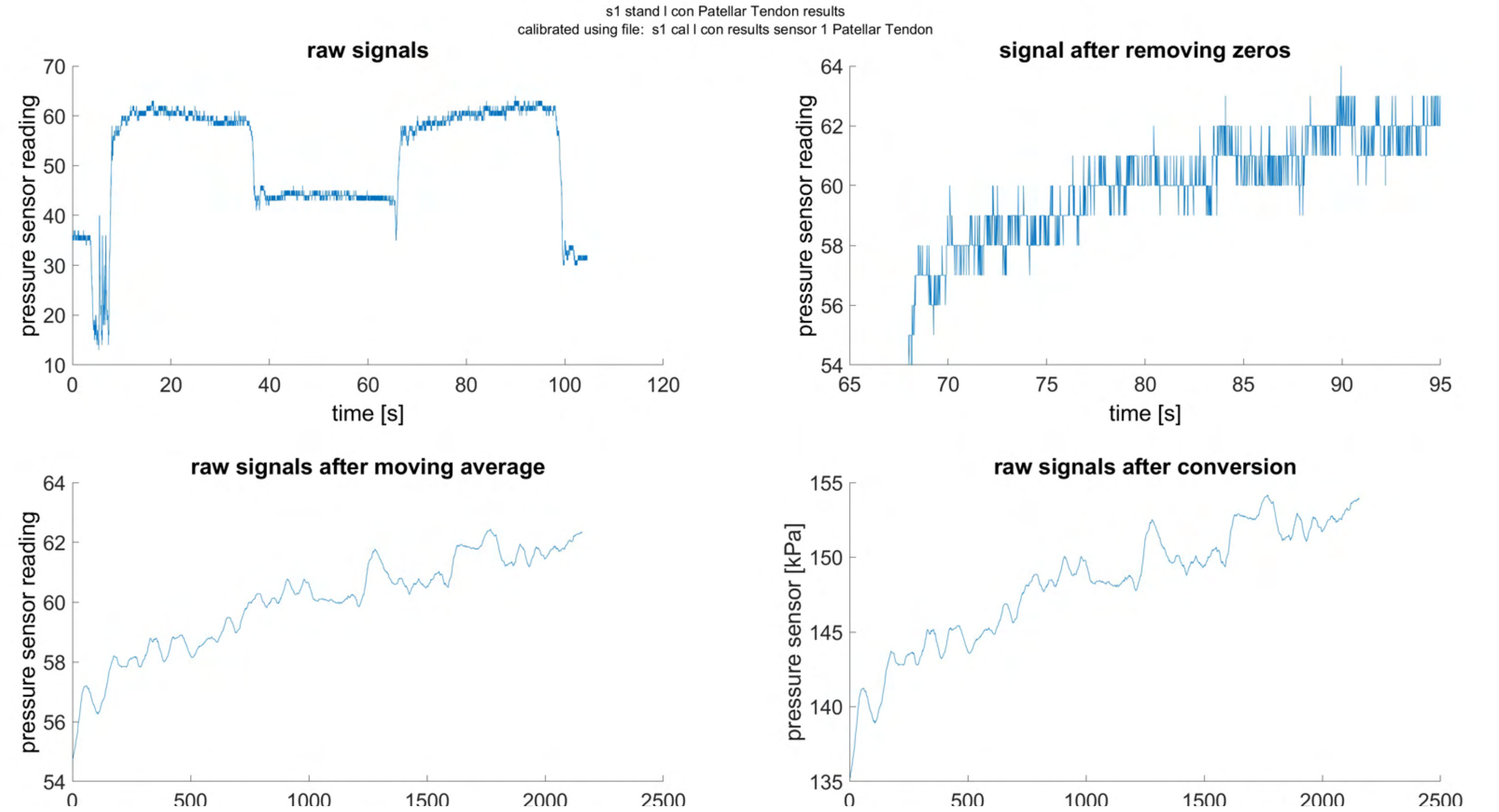
Calibrating FSR using the Indenter's load cell

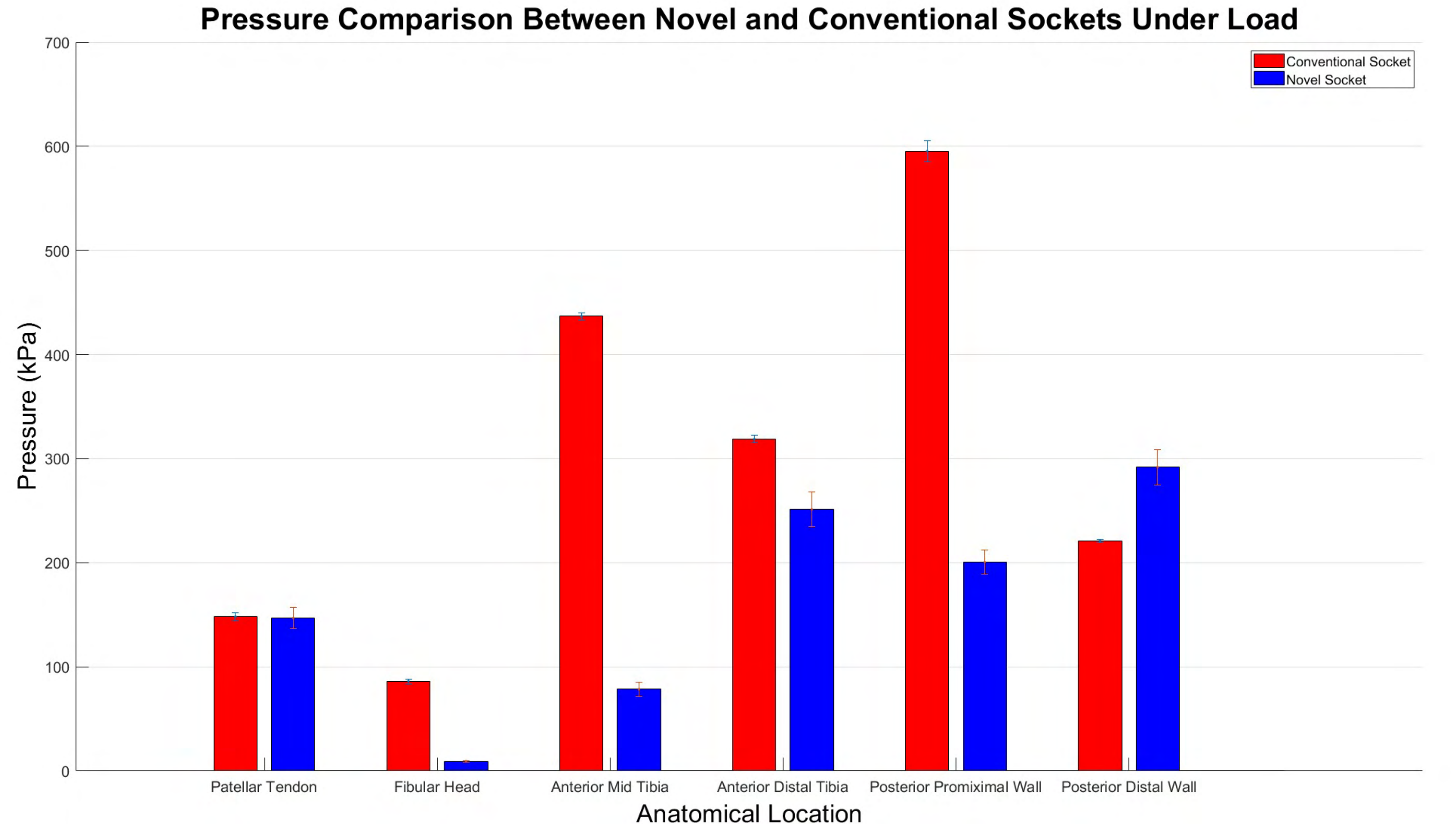
The final attempted sensor calibration method involved squeezing the Indenter on the FSR sensors placed on the limb. This had the potential to calibrate the sensors in-situ and account for any bending. It proved to be unreliable, yet was still an interesting project. To bar graph below required managing 24 datasets for calibration, applying the calibration results in the correct order to 12 raw data sets. Followed correctly importing 12 calibrated datasets in order into the graph.

FSR-Indenter Calibration Best Fit



Converting raw analog sensor data to calibrated pressure



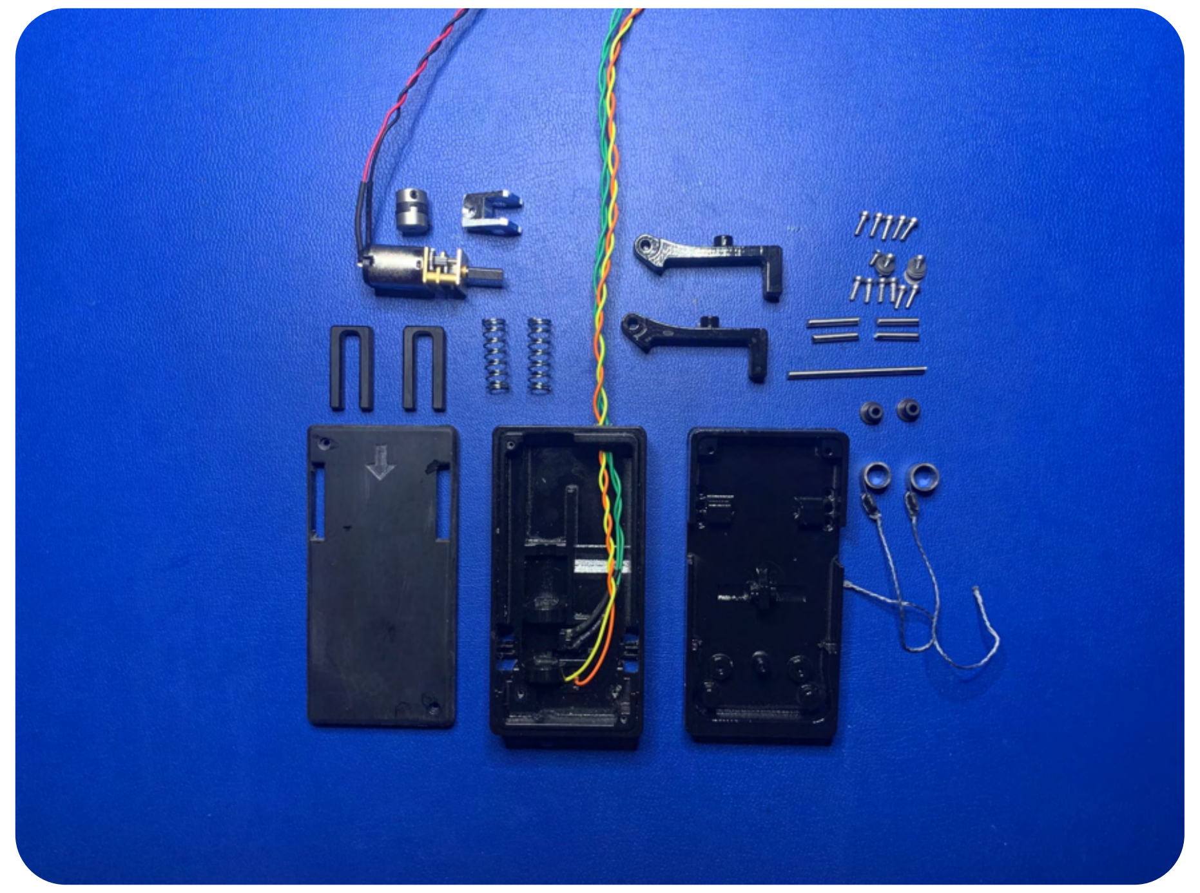


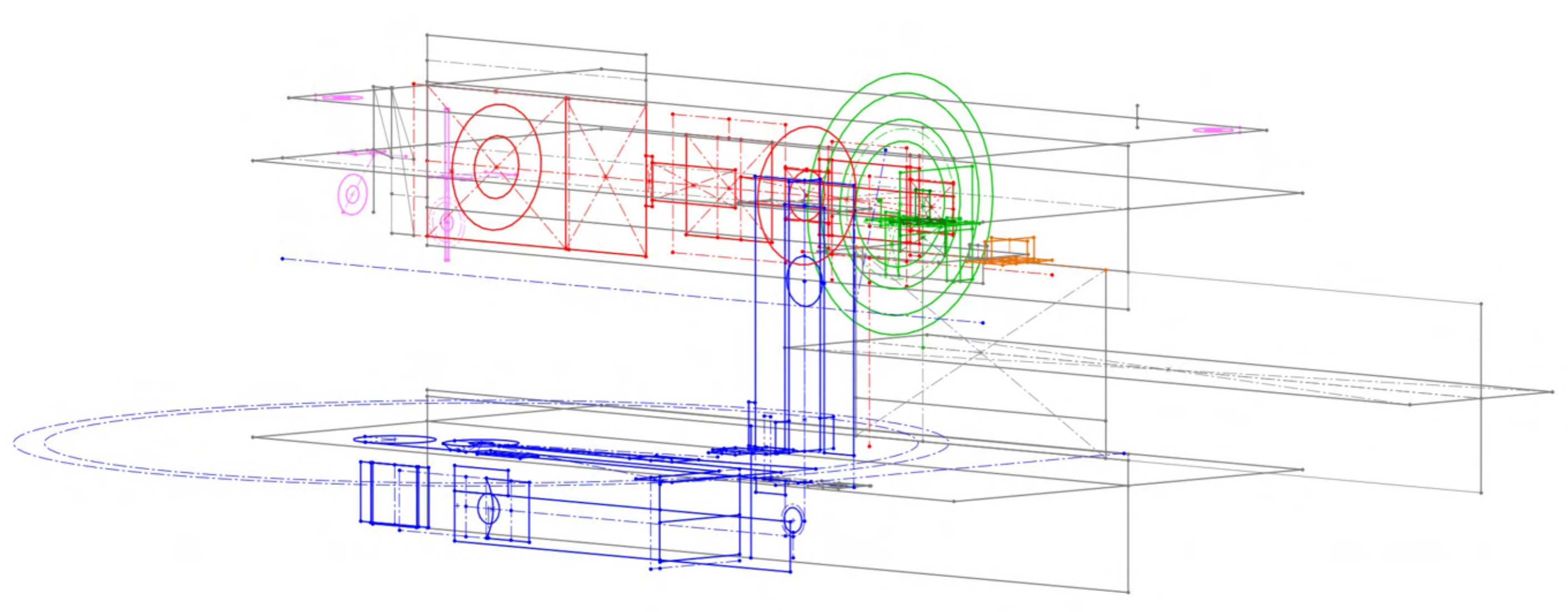
MIT Medical Device Design Course 2.75 – 2019

Project Objective:
Dr Ryan Carroll from Mass General Hospital presented the need for a device to precisely measuring blood oxygen perfusion.
Perfusion can help determine the severity of a health problem in cases of extreme dehydration, sepsis, and organ failure. Currently a doctor will pinch and release patient's finger and watch as the skin goes from a pale white back to a normal red. The time it takes for this transition is the capillary refill time (CRT) and is one method to determine perfusion.

Outcome:
My team demonstrated a small finger clip that could automate the process and produce precise time measurements CRT.

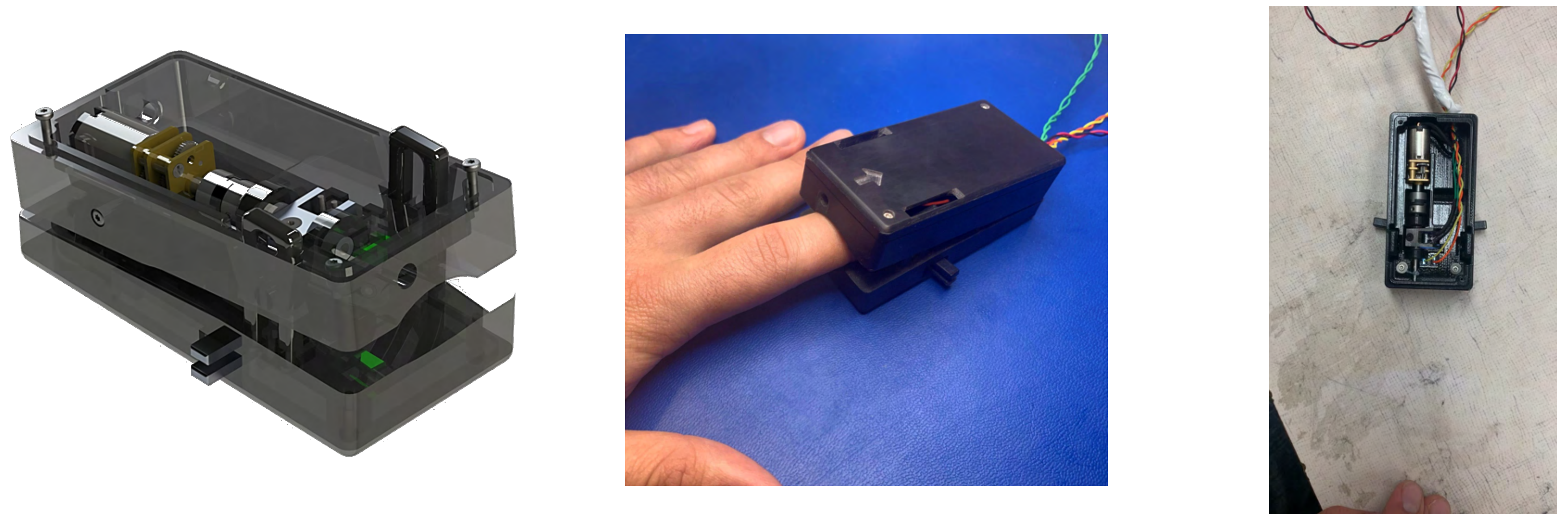
Team Role:
Team Leader, led experimentation planning, task formulation. Mentored less experienced teammates.
Responsible for the mechanical design.





Final Presentation Slides:

Our approach

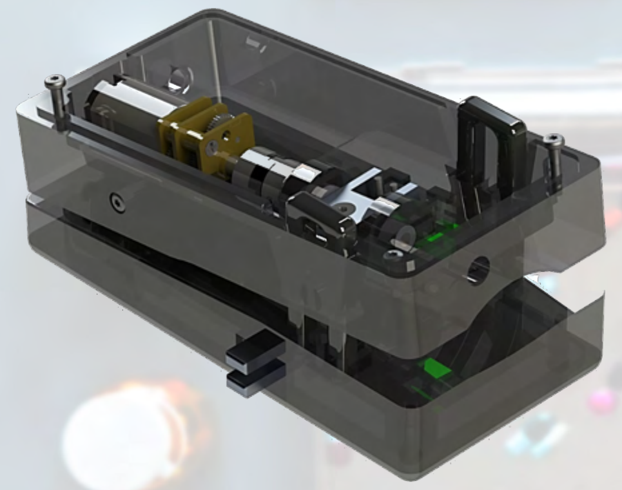


A **hand-held** device with exterior features similar to a pulse oximeter that applies **a certain force** to the **fingernail**, and measures CRT with a **photoresistor**.

Design description

Two modules:

- Sensor
- Pressure applicator



I. Sensor

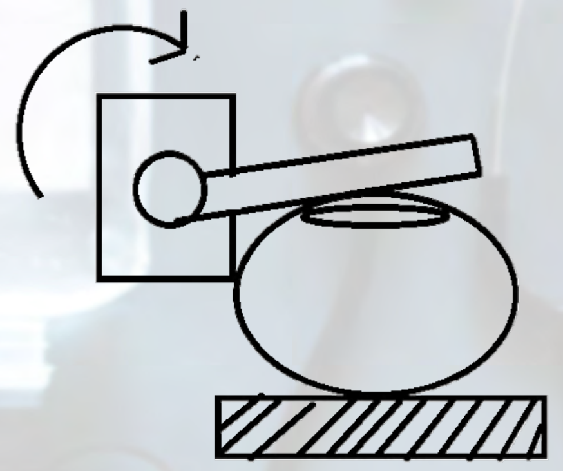
camera

photoresistor

impedance

Light intensity going through the photoresistor, placed above the nail, changes during the perfusion process.

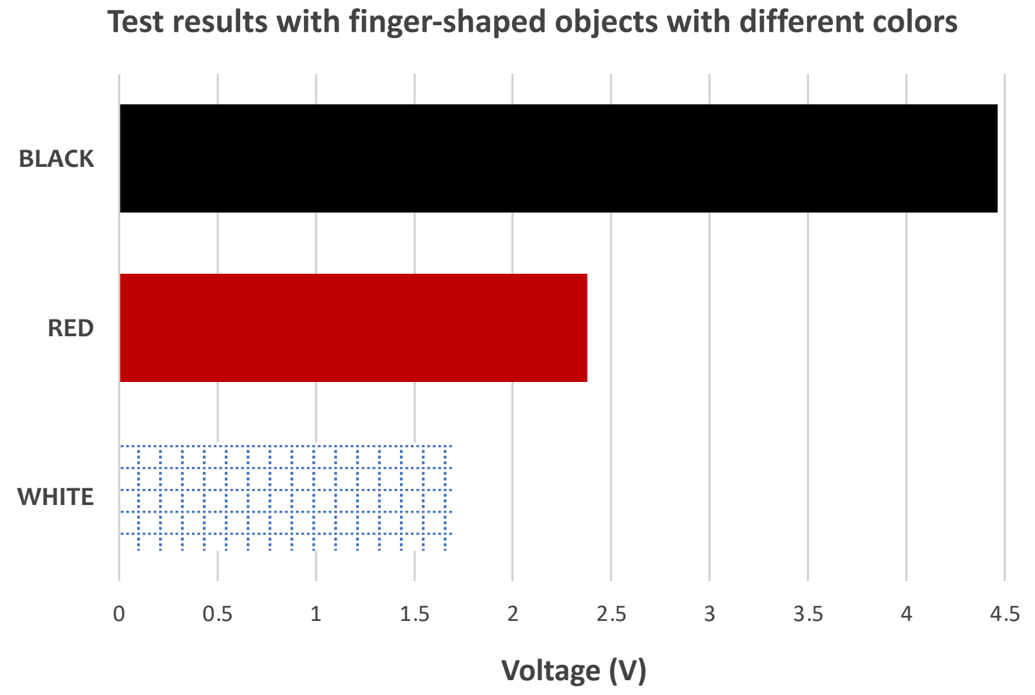
II. Pressure applicator



Force applied to the nail is driven by a motor.

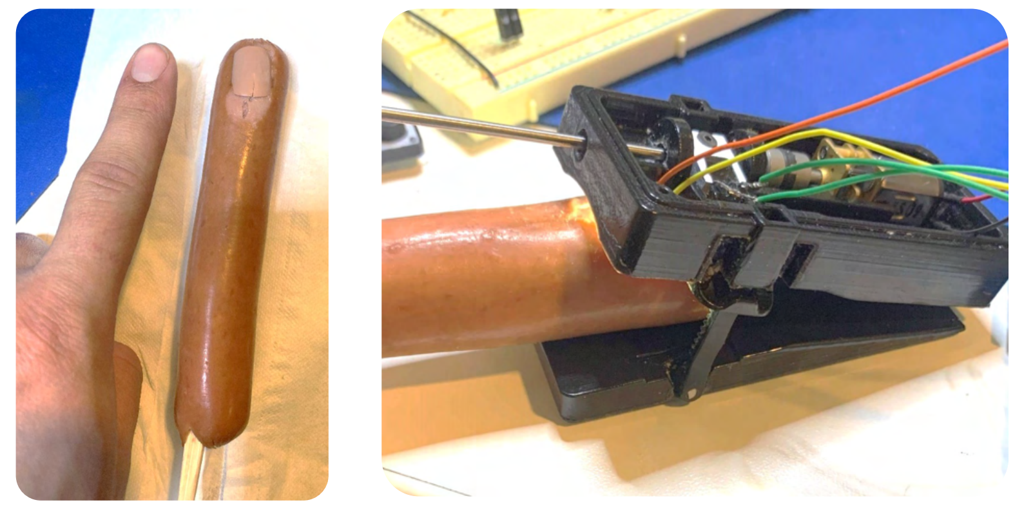
Test results
– how we made sure it measures CRT

I. Photoresistor can differentiate different colors.

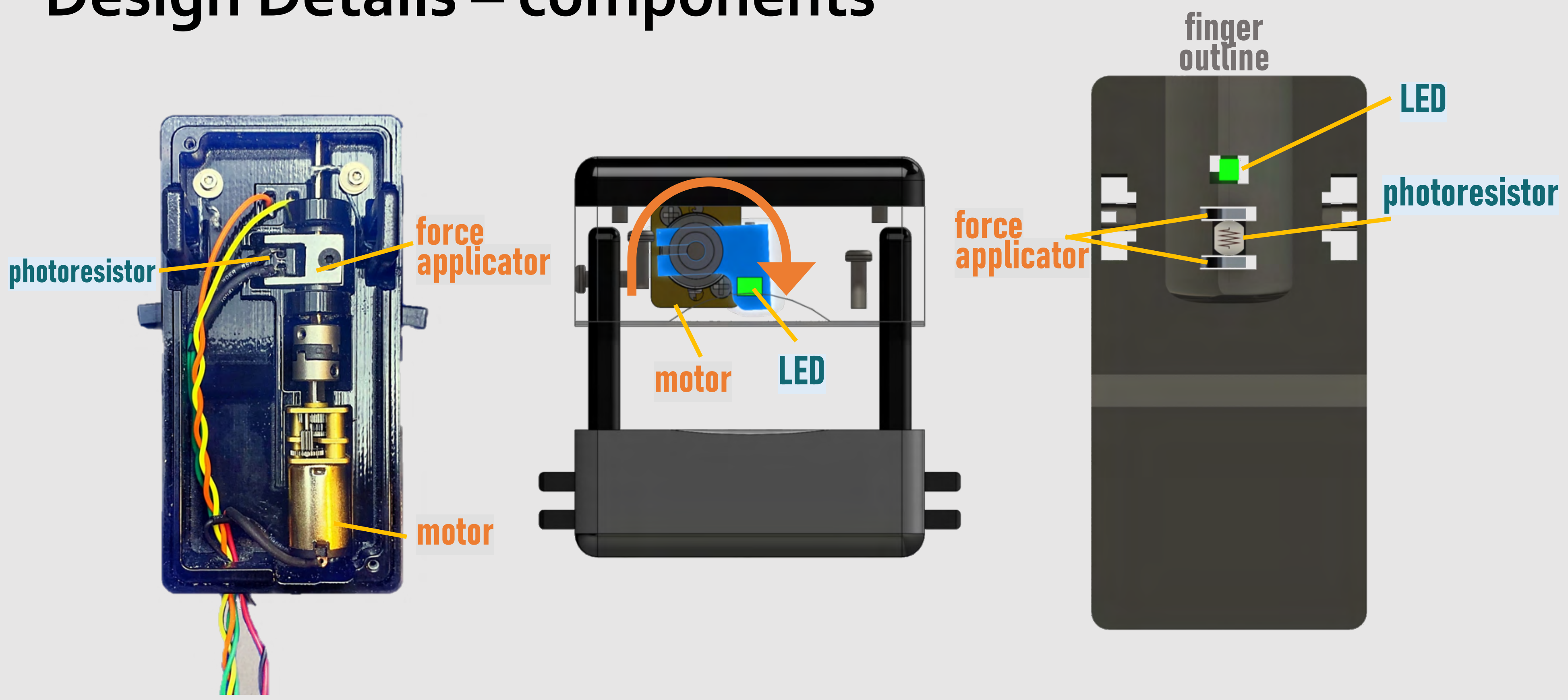

Test results with finger-shaped objects with different colors

II. Voltage difference as a result of movement is insignificant compared with that of color change.

phantom test #1: **hot dog**



Design Details – components

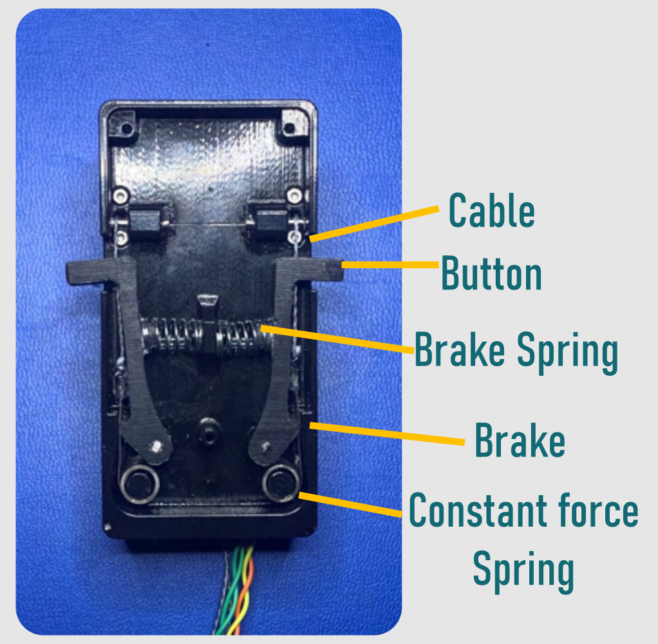


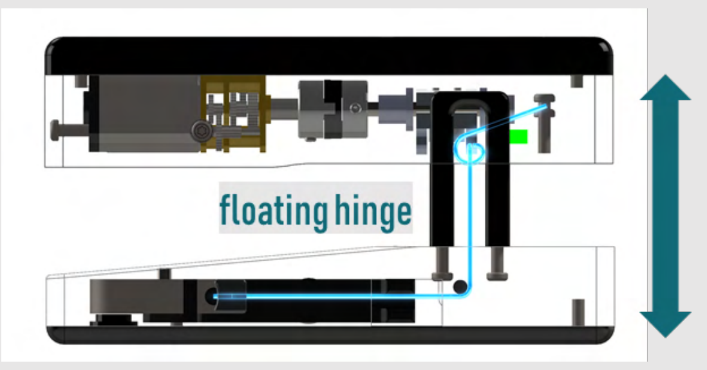
- View from the top

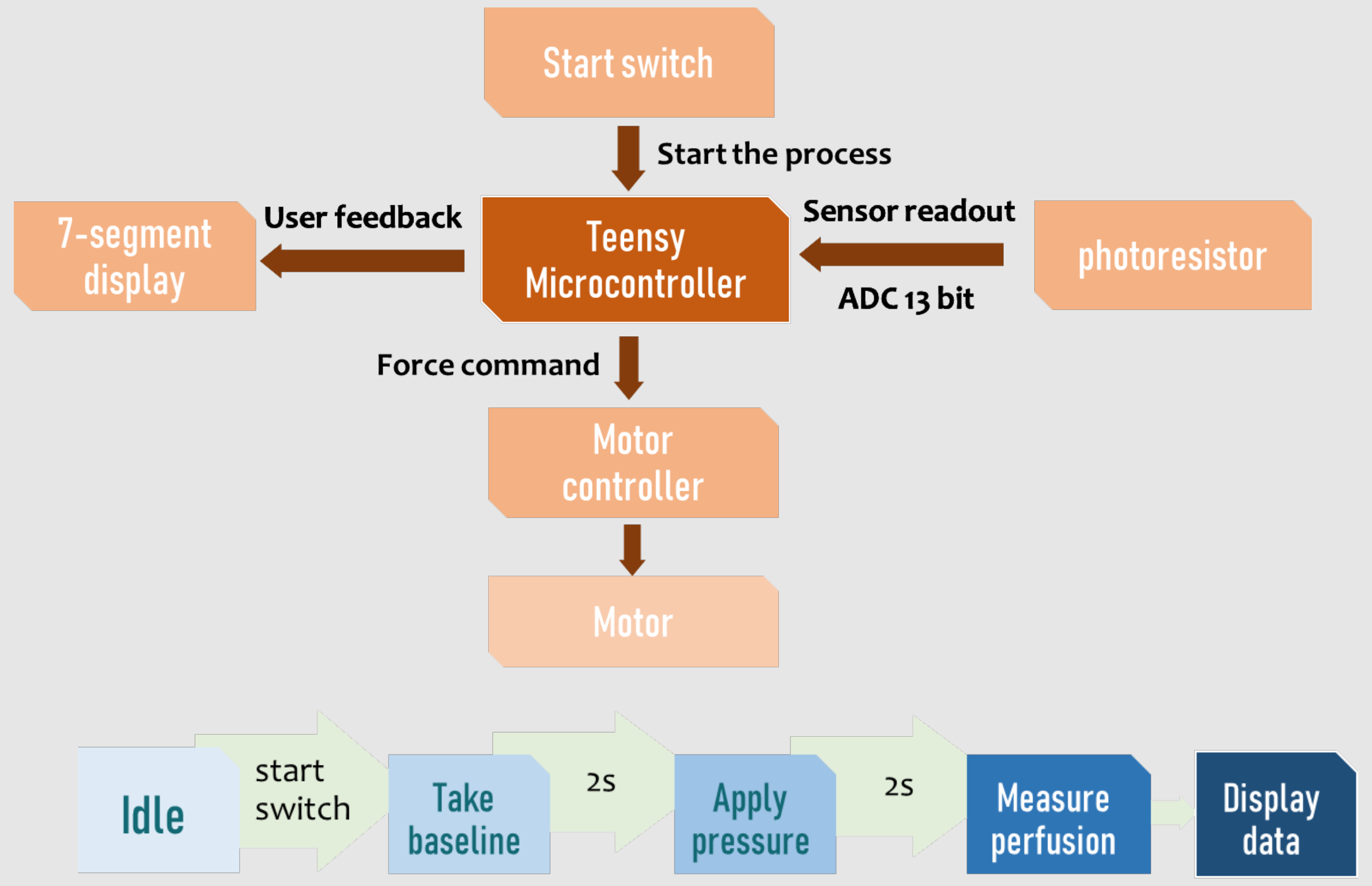
- View from the side

- View from the inside

Design Details – mechanical / electrical







Start switch

Start the process

Teensy Microcontroller

User feedback

7-segment display

Sensor readout

ADC 13 bit

photoresistor

Force command

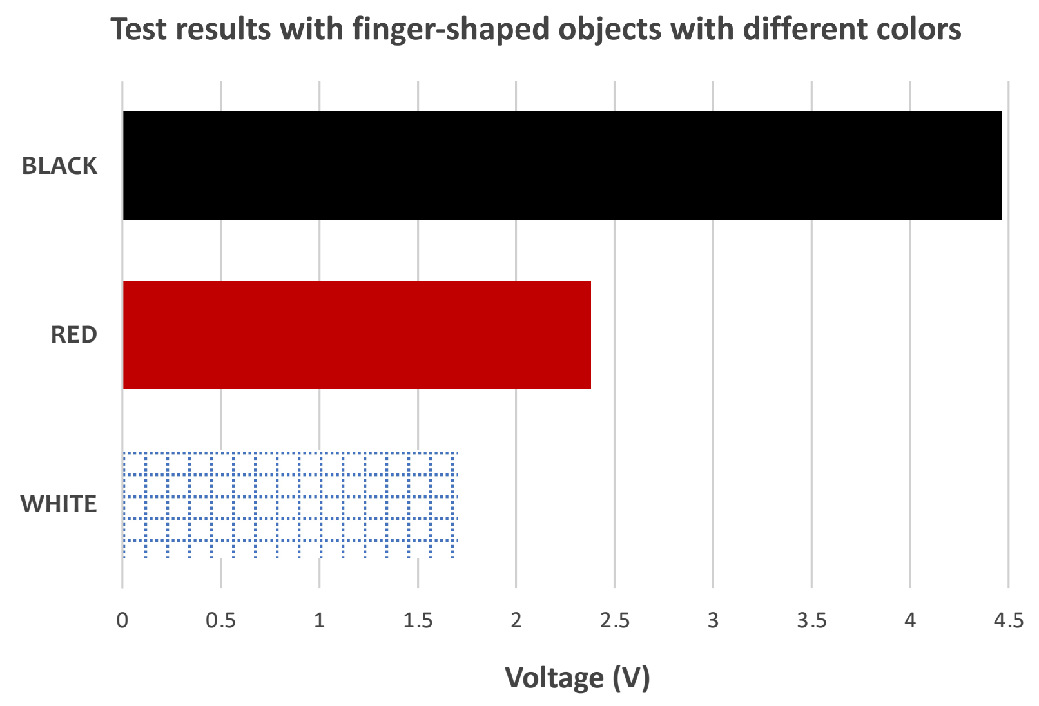
Motor controller

Motor

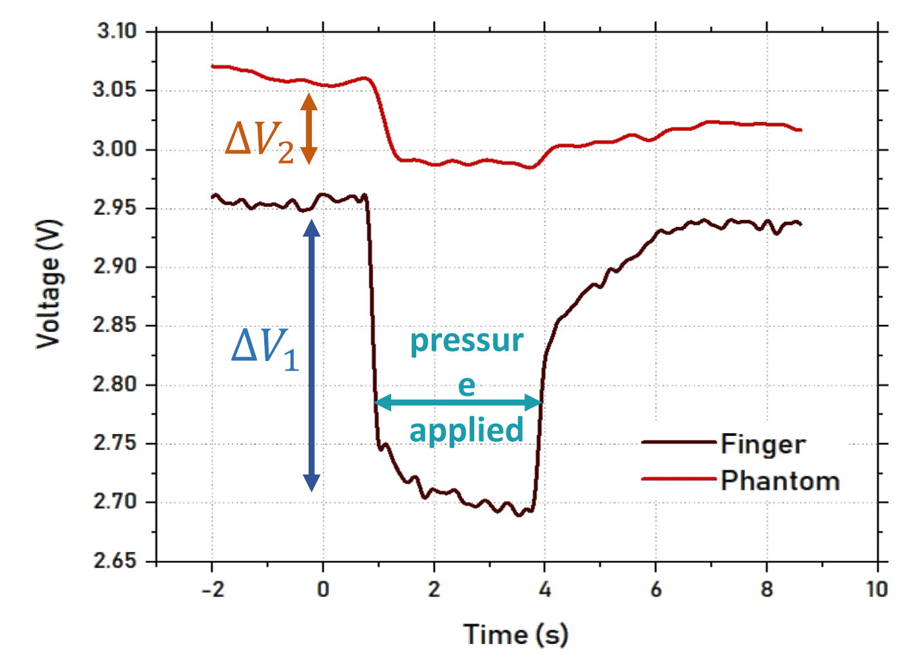
Idle → start switch → Take baseline → 2s → Apply pressure → 2s → Measure perfusion → Display data

Test results
– how we made sure it measures CRT

I. Photoresistor can differentiate different colors.


Test results with finger-shaped objects with different colors

II. Voltage difference as a result of movement is insignificant compared with that of color change.



$\Delta V_1 \approx 5\Delta V_2$

Markhor: Robotic Mining Platform – WPI 2017

Domenic Bozzuto (RBE, CS), Rene Jacques (RBE), Aaron Jaeger (RBE),Brian Peterson (ME), Yu-sen Wu (RBE, ME)
Advisors: Michael Ciaraldi, Kenneth Stafford

Project Goals:
Design and build robot to compete in the NASA Robotic Mining Challenge capable of in a Martian environment and collecting and depositing 100kg "icy" Regolith (crushed basalt and gravel).

Roles:
Prototyped and experimented with new mechanism designs. Used testing results to inform design revisions. Machinist. Resource coordinator. The "glue" of the team.

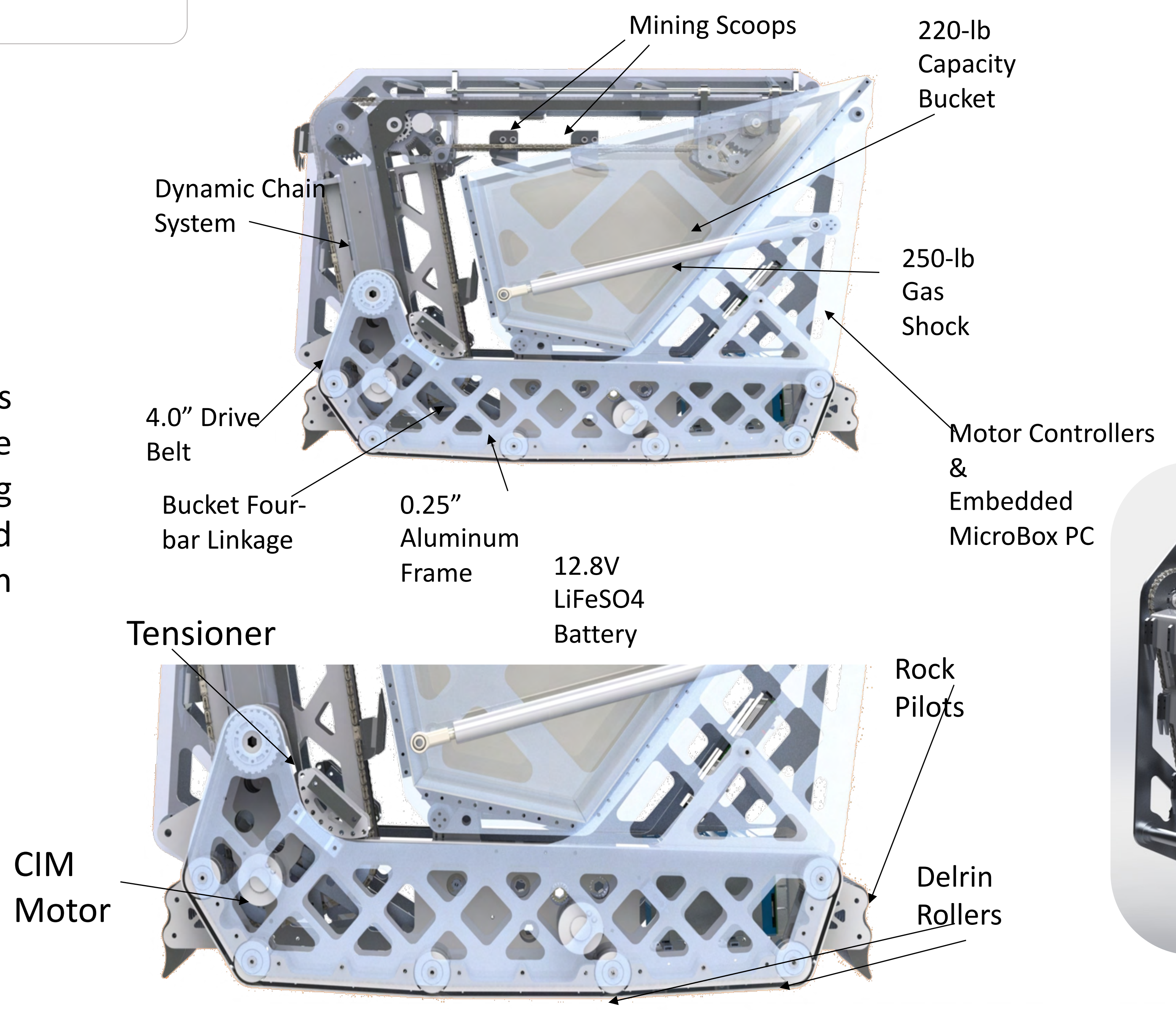
Demo and project presentation: [Google Drive Presentation]
Additional Competition info [NASA]

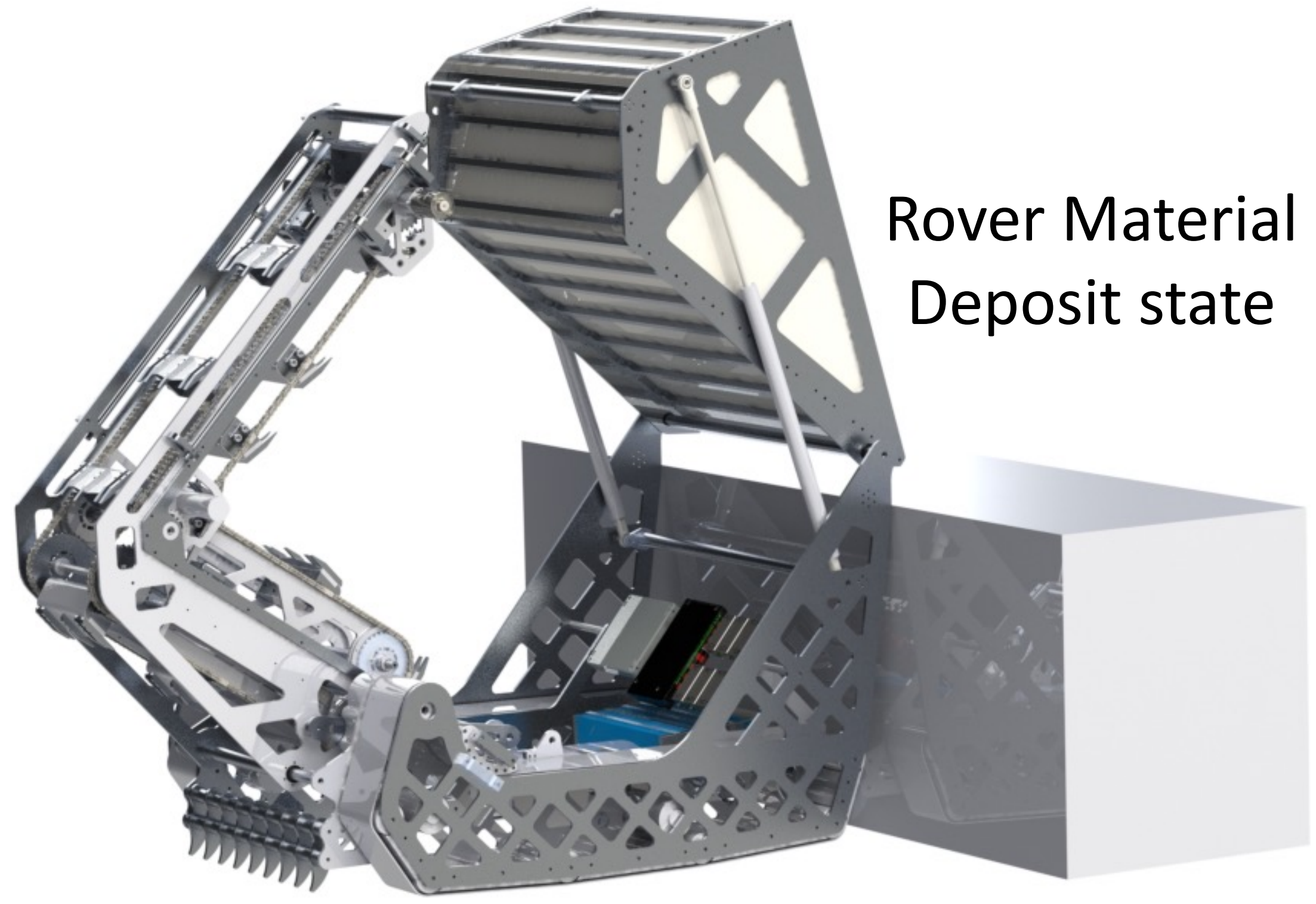
Abstract
In-situ resource utilization, or the use of the resources available in a foreign environment, is crucial to the success of manned missions to Mars; however, it is a severely underdeveloped technology. This project explores the development of a rover capable of operating in a simulated Martian environment. The rover is capable of mining large amounts of simulated ice chunks from below the surface, driving its payload to a collection station, and unloading all the collected material. This project is partially inspired by NASA's Robotic Mining Competition which served to establish a set of guidelines around which the robot was constructed.

Collection System

Our early collection prototypes taught us three important things. First breaking through the surface of gravel requires a lot of pressure, and the teeth on the scoops cannot be in a line. Second breaking through dirt and gravel causes a big disturbance, if the scoop is dragged through the gravel in a line after initial breakthrough then we can collect more material. Third, bucket ladder systems are very efficient at digging, however, can be fragile. Having the scoops follow a guide track transfers the digging load from the scoops to the track rather than the scoop to the chain.

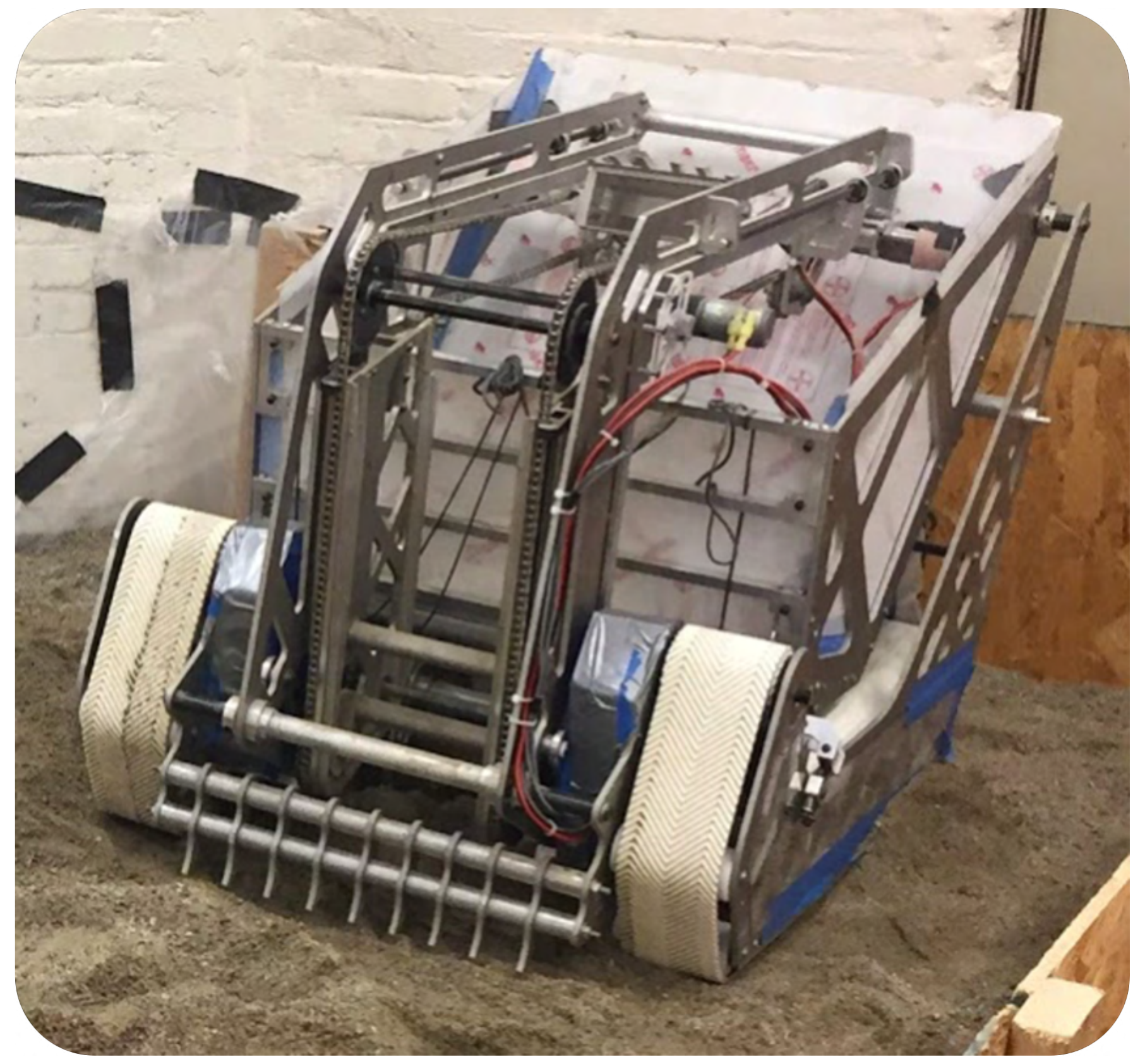
When transferring material from scoops to bucket the scoops are rotated beyond 60 degrees due to the high cohesion of regolith





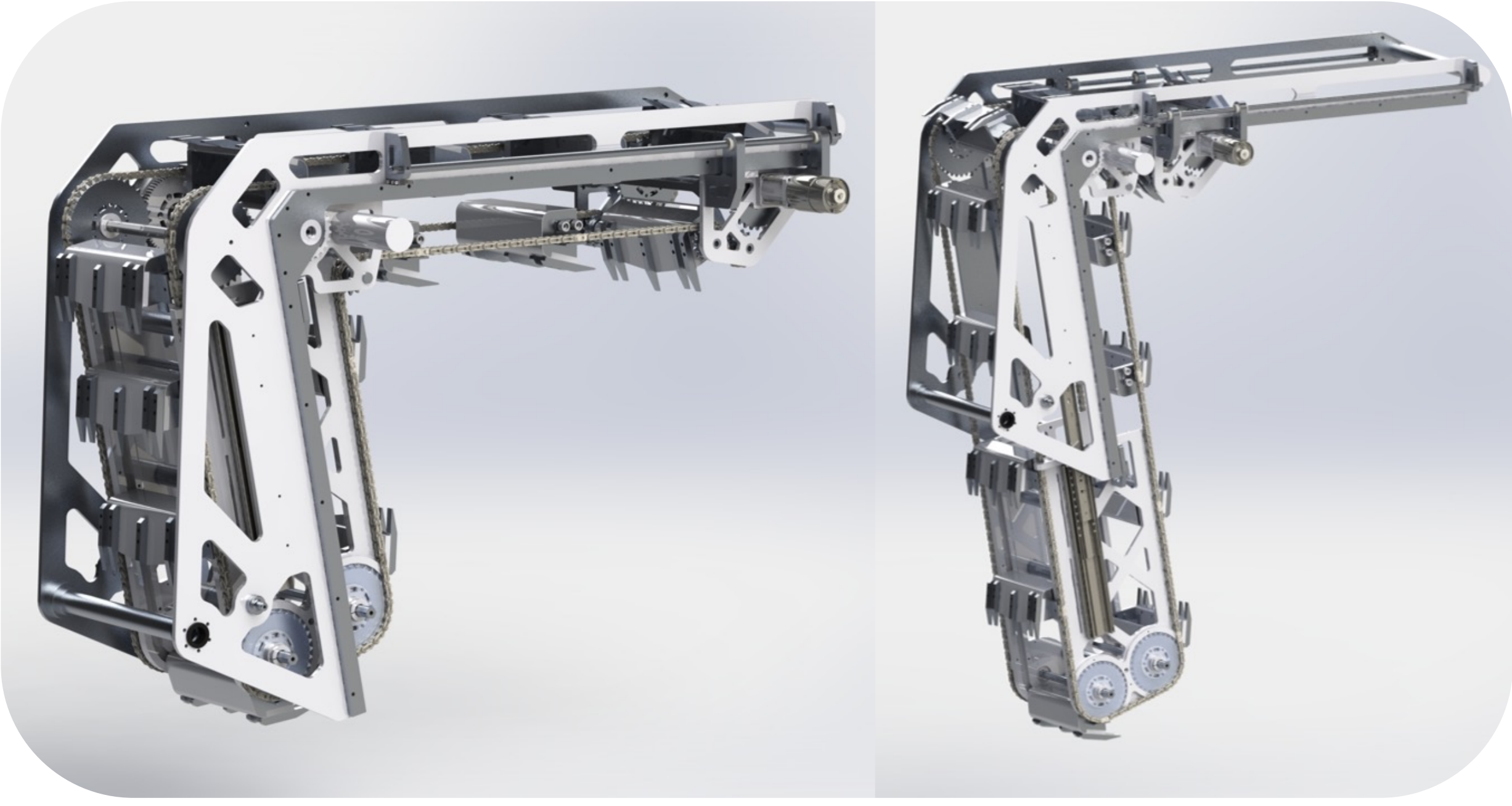
Rover Material Deposit state

Lifting 100kg of material requires a lot of energy, and heavy, slow and expensive linear actuators. As a joke I suggested using a winch to lower the bucket lifted by a fully passive gas-shock lift system the bucket.



Markhor (front) during testing

Specifications	
Dimensions (LxWxH)	40in x 28in x 29in
Weight	80 kg (176 lbs.)
Rated Payload	100 kg (220 lbs.)
Maximum Speed	0.254 m/s (10 in/s)
Operating Time	10 min
Material Collection Rate	0.4 kg/s (14 oz/s)
Collection Depth	0.4 m (16 in)



Dynamic Chain collection system, compressed and extended state

Top: Markhor (back) at RMC
Bottom: Markhor depositing Regolith

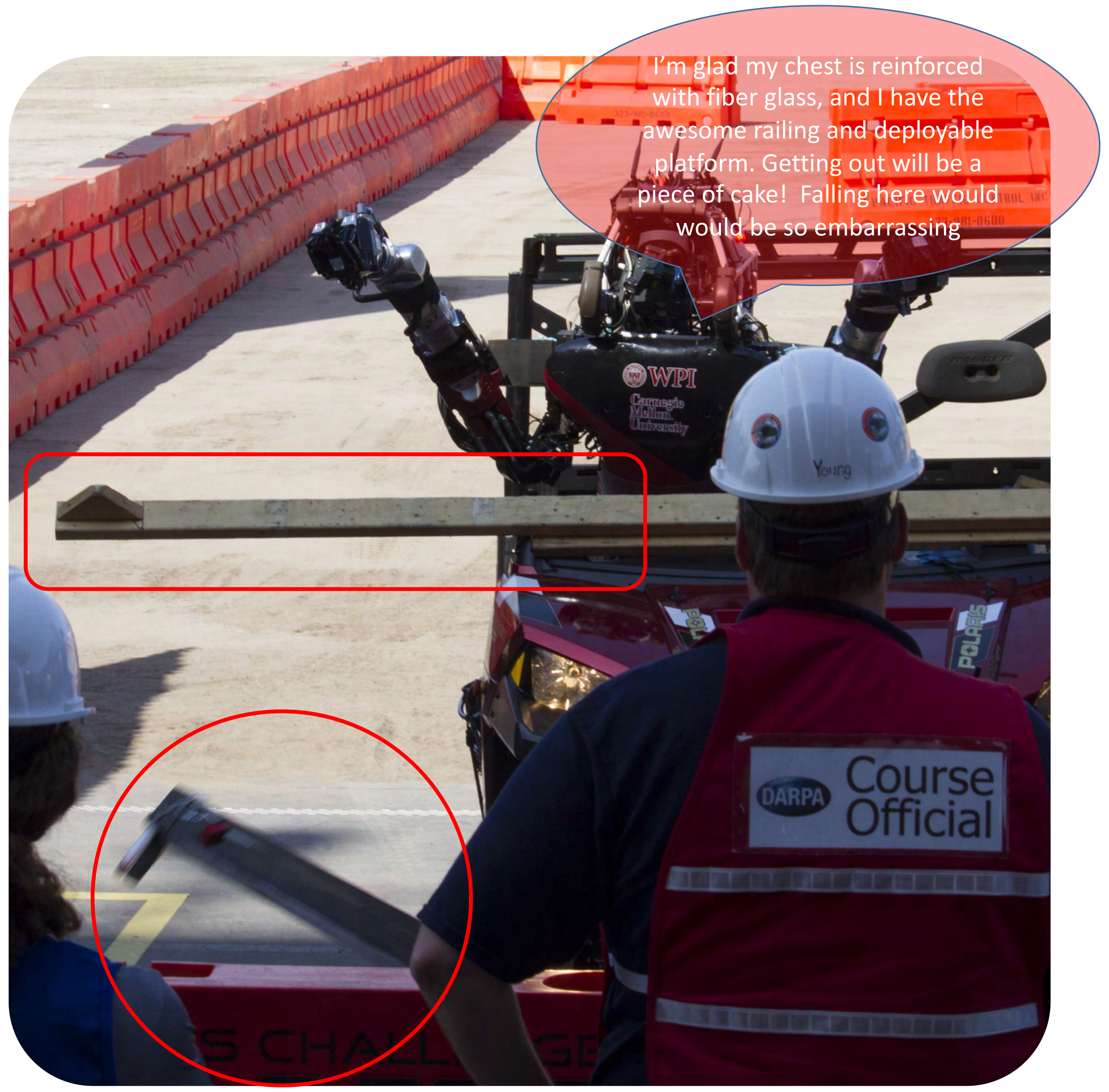
Negotiated interdepartmental cooperation to convert Professor Bergstrom's office into simulated Mars test facility with two tons of sand.

WPI-CMU Darpa Robotics Team – 2014-2015:

Project:
WPI competed in the Darpa Robotics Challenge developing robotic disaster response capabilities.

Outcomes:
WPI's Atlas robot completed 7/8 of the competition tasks. WPI was the only team that did not fall and require a reset.

Project Role:
Undergraduate Research Assistant. Member of User Interface, robot testing, and robot maintenance teams. Responsible for robot egress hardware and aftermarket sensors.

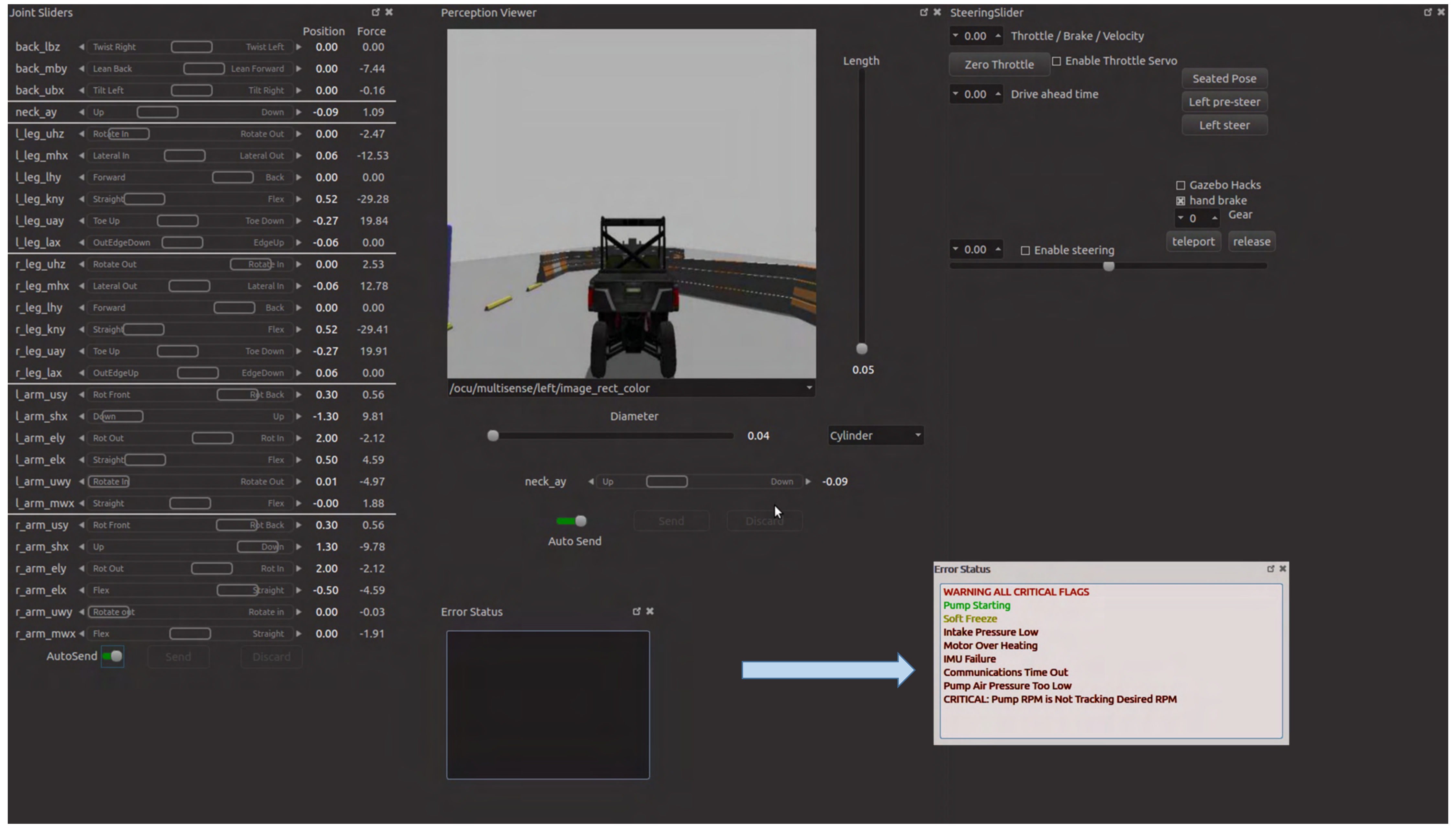


Atlas car egress with the help of assistive car additions
#NOFALLSNORESETS

Atlas Walking Through Door

Operator Controlling Robot

My ROS GUI Widgets



Error Status
WARNING ALL CRITICAL FLAGS
Pump Starting
Soft Freeze
Intake Pressure Low
Motor Over Heating
IMU Failure
Communications Time Out
Pump Air Pressure Too Low
CRITICAL: Pump RPM is Not Tracking Desired RPM

Widgets:

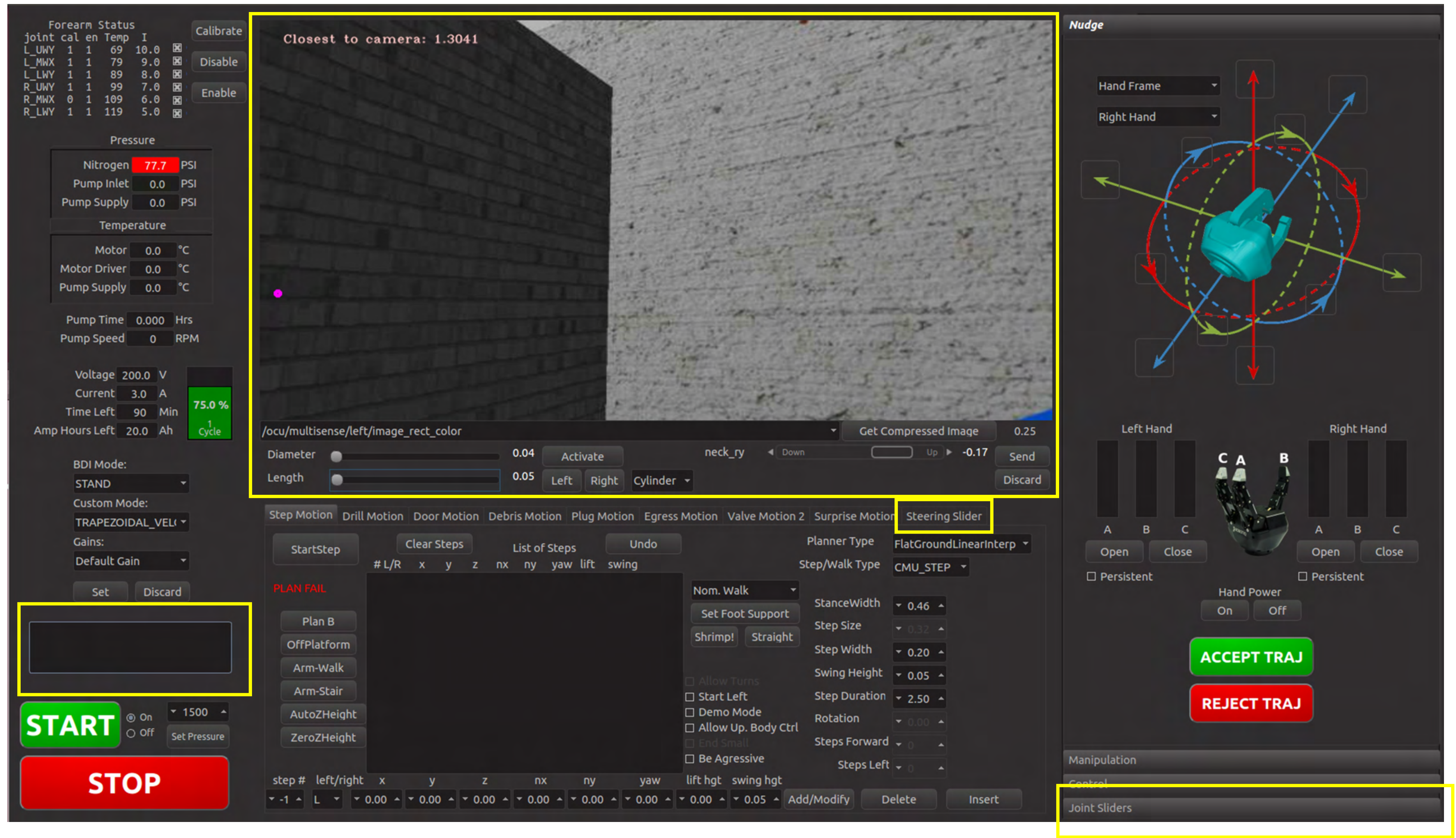
Joint Sliders
- Joint sliders display live joint angles and torques
- Sliders also allow user to manually set joint angle
- Angle and torque change color when approaching their limits

Error Status
- Parses error codes
- displays human readable critical system faults

Perception viewer
- Perception viewer displays selected camera views
- Allows user to move head angle without opening joint sliders widget
- Allows user to set parameters for object selection

Steering slider
- widget used for Atlas to drive the car
- The widget was added to include additional features after my initial development

My Widgets Located Within the Robot Control GUI



MIT Media Lab – 2016:
Project Express

Project Goal:
A design framework to allow for self expression through painting adaptable to any physical limitations.

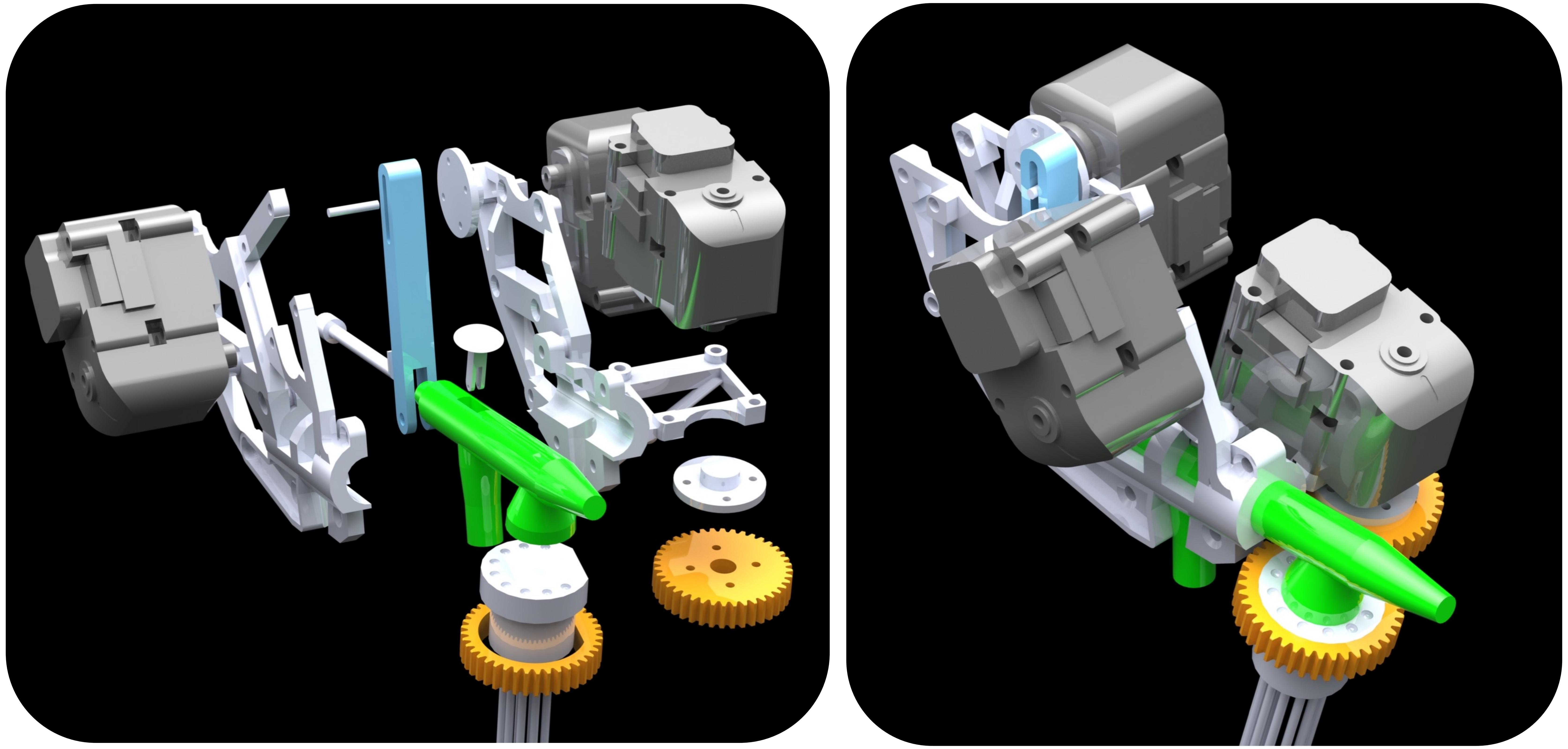
Contributions:
Designed the hardware attachments to robotically control an airbrush.
Evaluated performance requirements for the motor and linear screw for the x-y gantry designed to move the airbrush across the canvas.

Role:
Unofficial visiting student for Tal Achituv's Master's thesis during winter break.

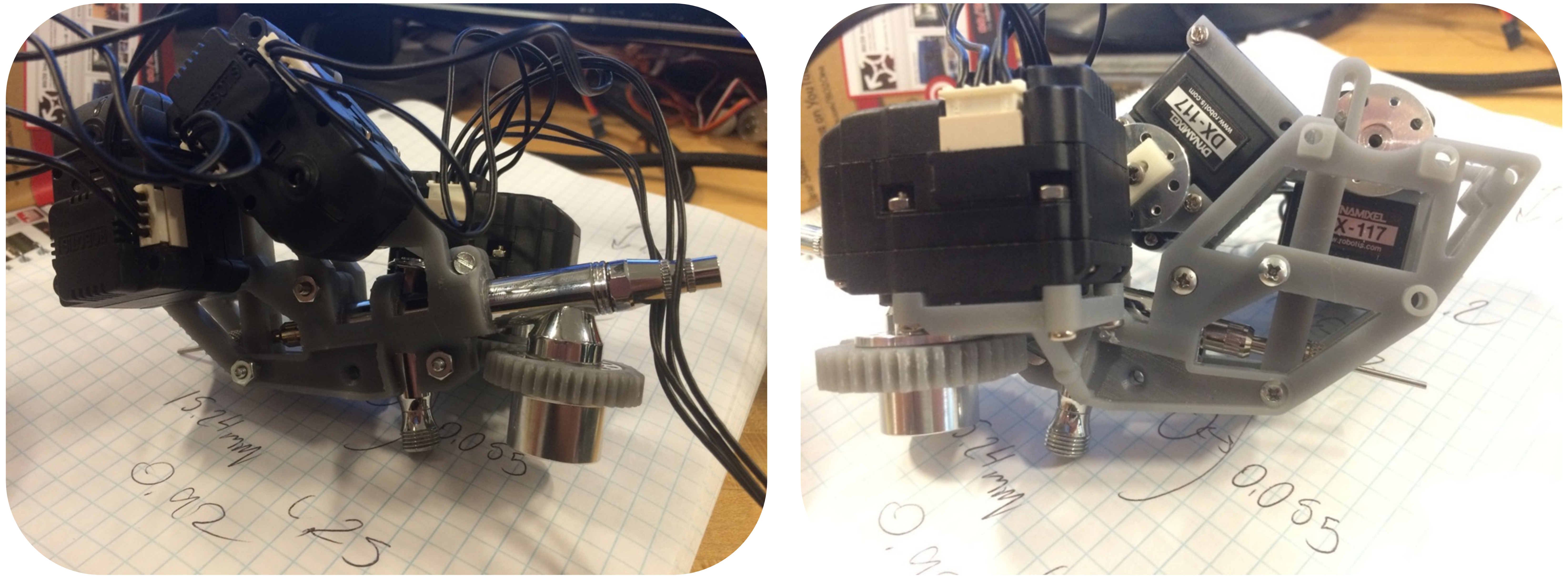
Tal's Thesis:
http://hdl.handle.net/1721.1/106064

Samples of artwork enabled by robotically controlled Airbrush and gantry

CAD Screenshots



Airbrush Attachments Assembled



All photos courtesy of Tal Achituv

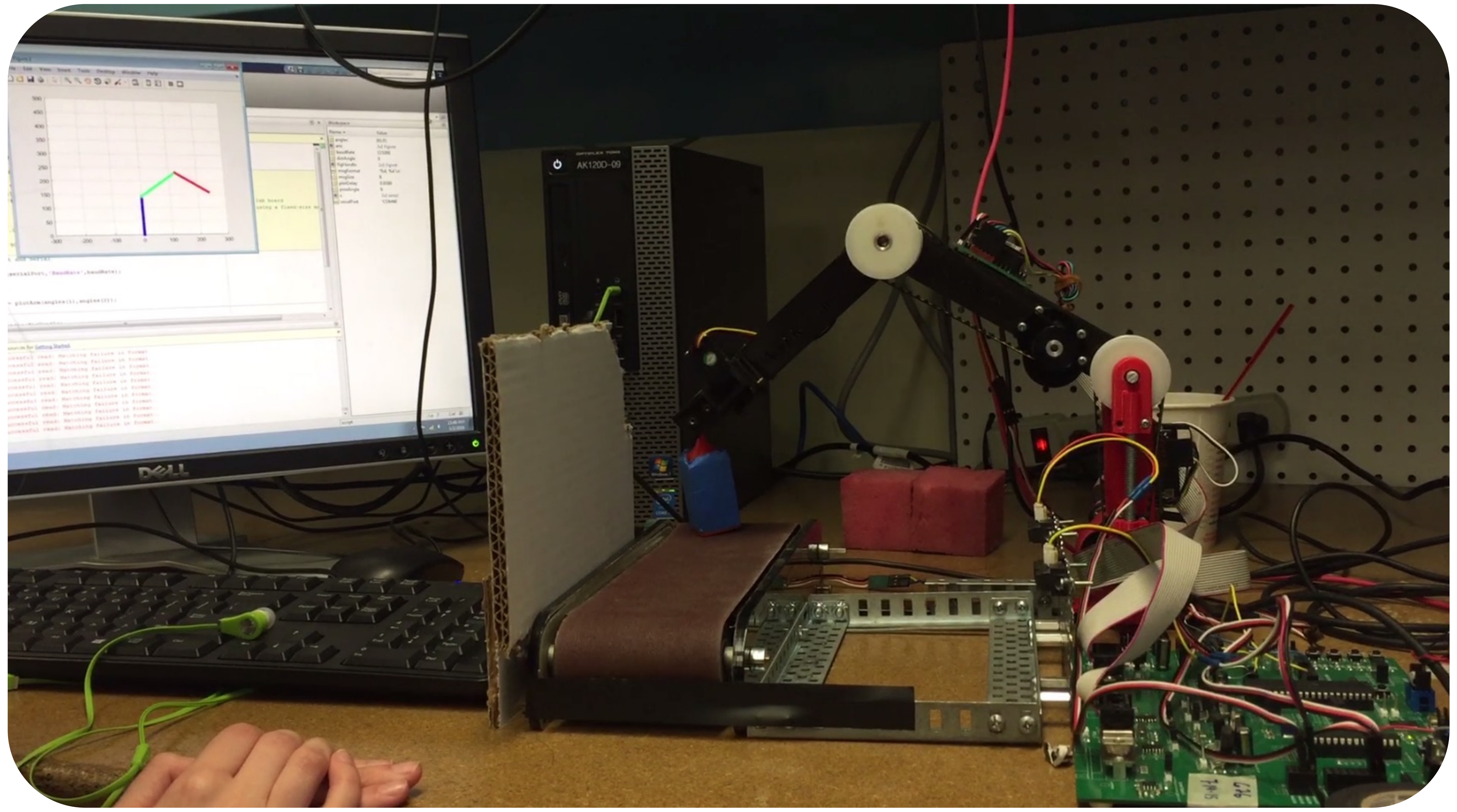
WPI Robotics Engineering (RBE) Course 3001 – 2016

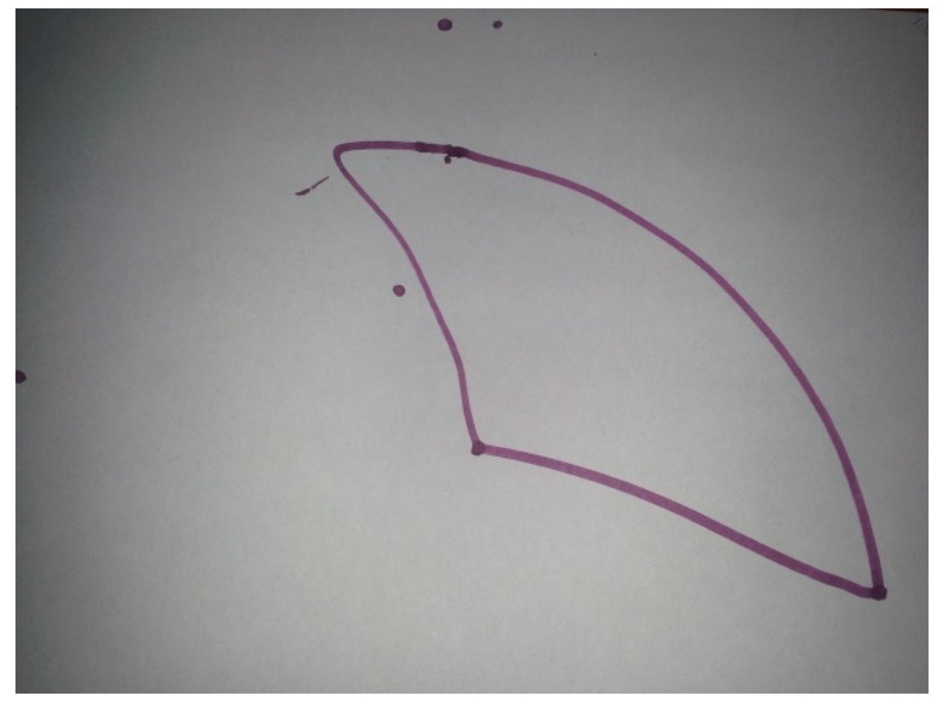
Project: Programmed position control of 2 degree of freedom robotic arm on embedded system. Arm capable of sorting blocks by weight. Demo Video.

Contributions: Inverse kinematic solver and PID control loop.

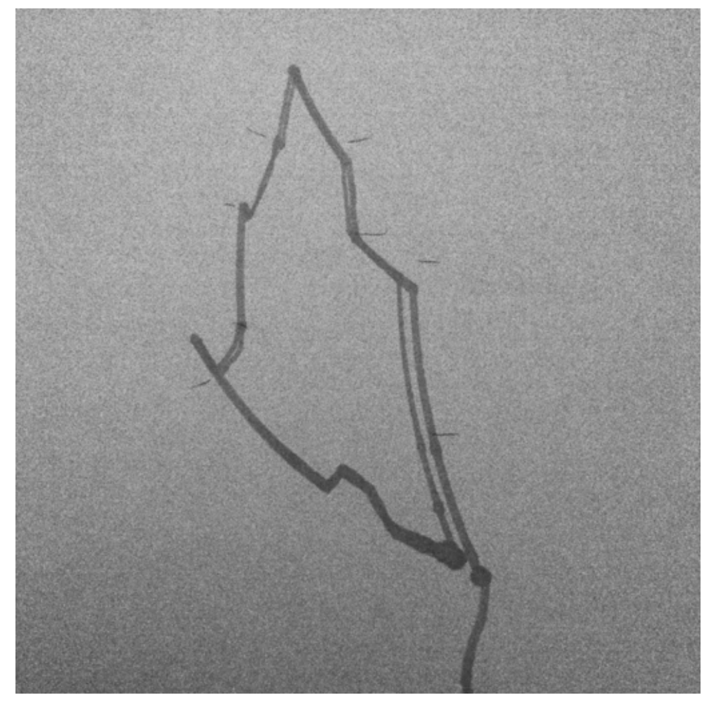
Project type: WPI class project. This project, and the WPI projects on the following slides were completed in the last 2-4 weeks of a 7 week course on 3-4 person teams.

2 DOF Robot Arm





Triangle drawn only going to coordinates of endpoints



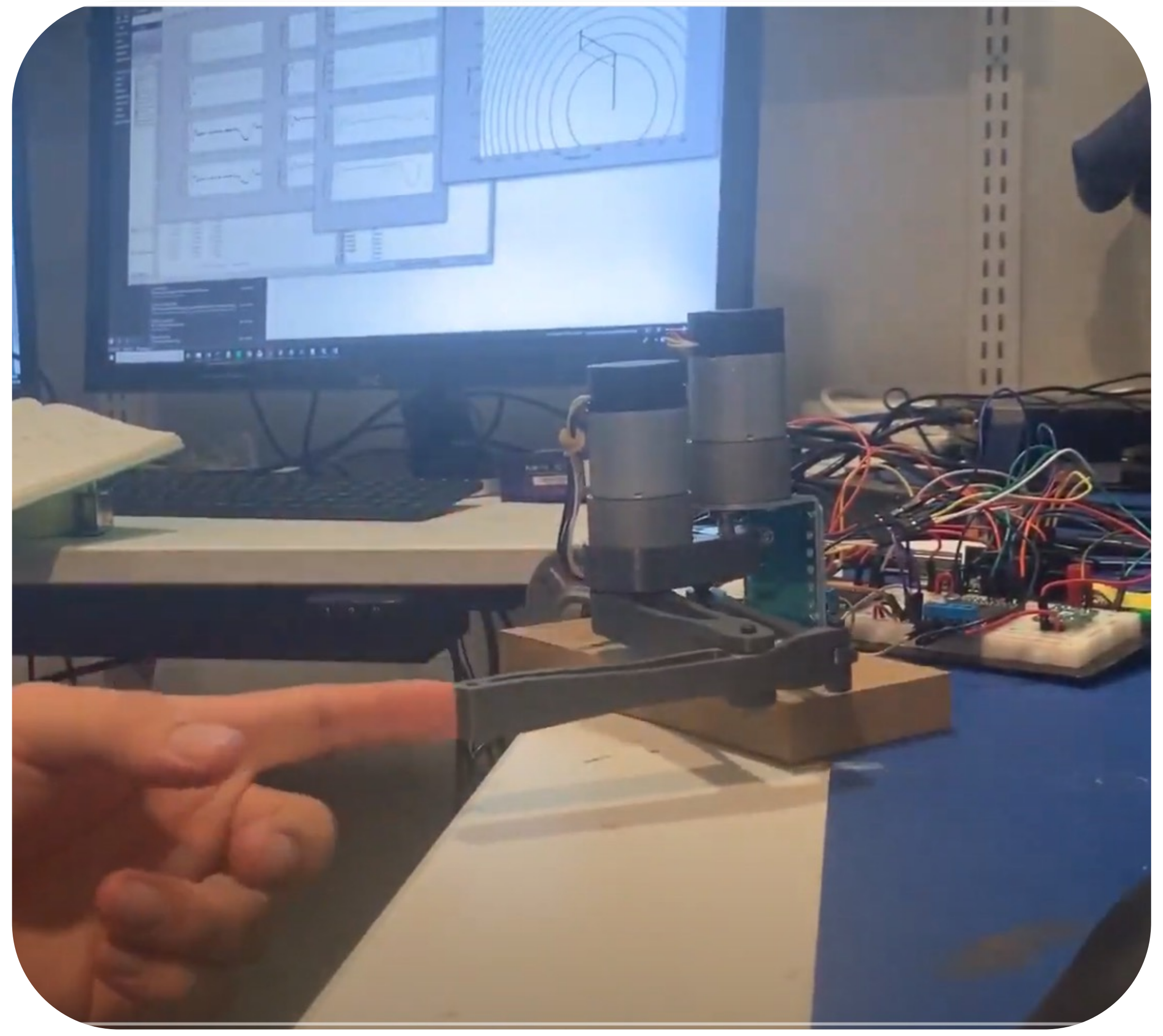
Triangle drawn going to intermediary points.
2DOF life is rough

MIT 2.74 Bio-Inspired Robotics – 2019
Prof. Sangbea Kim
2 DOF Legs Revisited

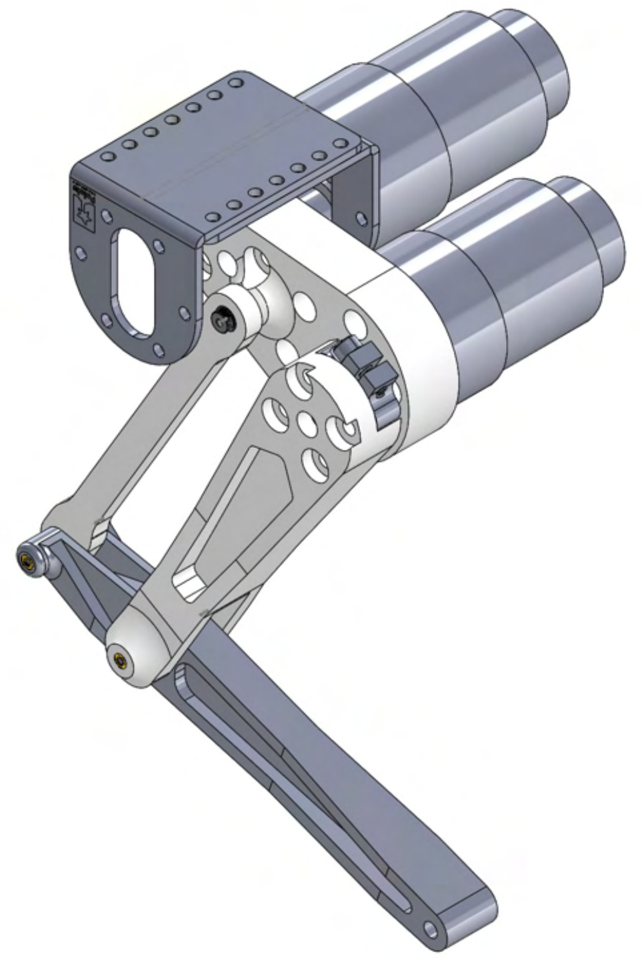
Labs focused on impedance controllers and using the current draw of the motor in addition to the encoder position as the control inputs for the for actuator.

The assignments were to implement various control schemes, then playing with the parameters to explore their effect on the behavior.

Testing the Robot Leg

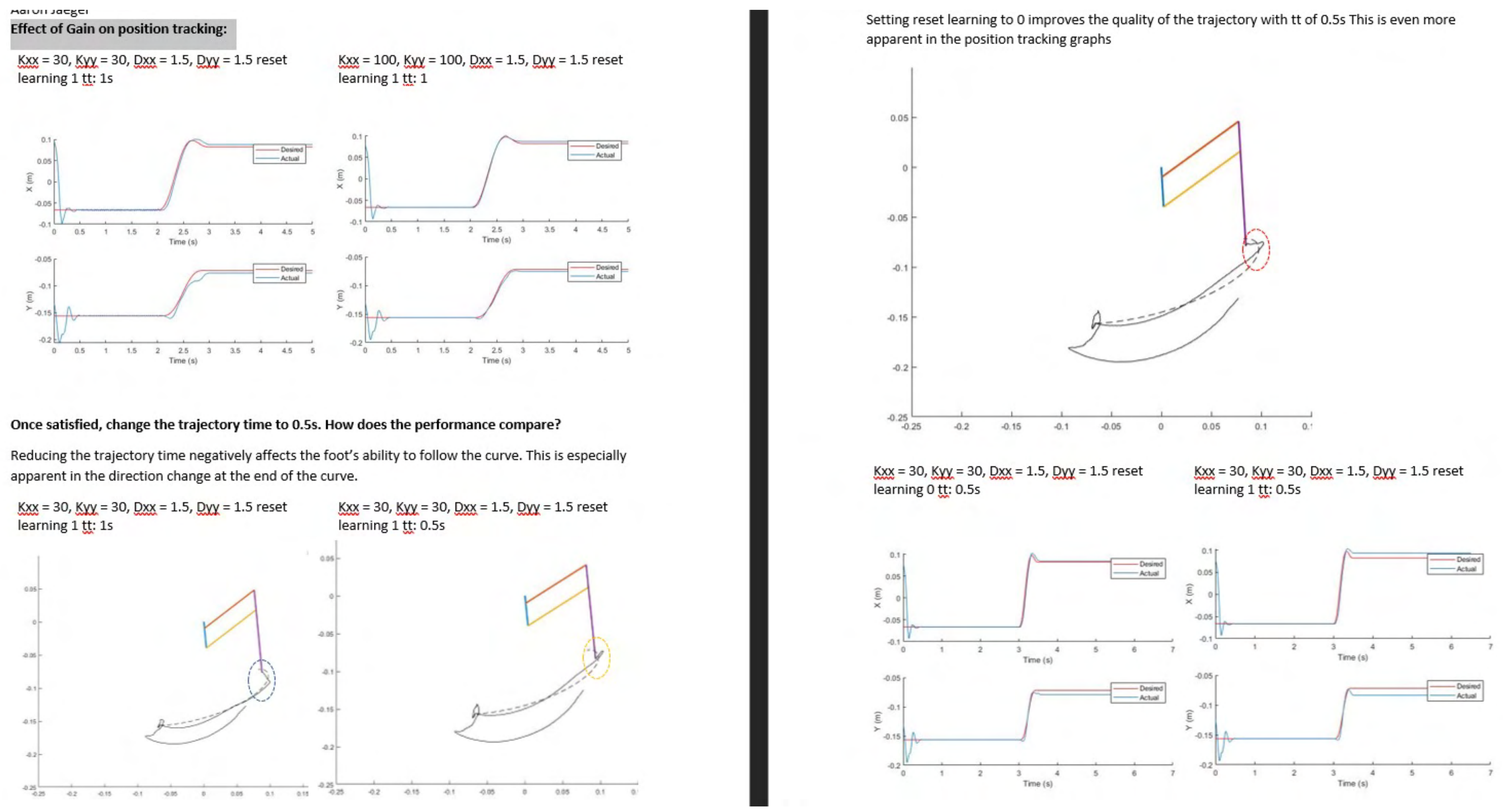


The final project was open ended. My four-person team explored manual turning vs simulation-based tuning for a robot dropped from two feet.



2 DOF parallel robot leg used for class assignments

Exploring Control Parameters



Effect of Gain on position tracking:

Kxx = 30, Kyy = 30, Dxx = 1.5, Dyy = 1.5 reset learning 1 tt: 1s

Kxx = 100, Kyy = 100, Dxx = 1.5, Dyy = 1.5 reset learning 1 tt: 1

Once satisfied, change the trajectory time to 0.5s. How does the performance compare?

Reducing the trajectory time negatively affects the foot's ability to follow the curve. This is especially apparent in the direction change at the end of the curve.

Kxx = 30, Kyy = 30, Dxx = 1.5, Dyy = 1.5 reset learning 1 tt: 1s

Kxx = 30, Kyy = 30, Dxx = 1.5, Dyy = 1.5 reset learning 1 tt: 0.5s

Setting reset learning to 0 improves the quality of the trajectory with tt of 0.5s This is even more apparent in the position tracking graphs

Kxx = 30, Kyy = 30, Dxx = 1.5, Dyy = 1.5 reset learning 0 tt: 0.5s

Kxx = 30, Kyy = 30, Dxx = 1.5, Dyy = 1.5 reset learning 1 tt: 0.5s

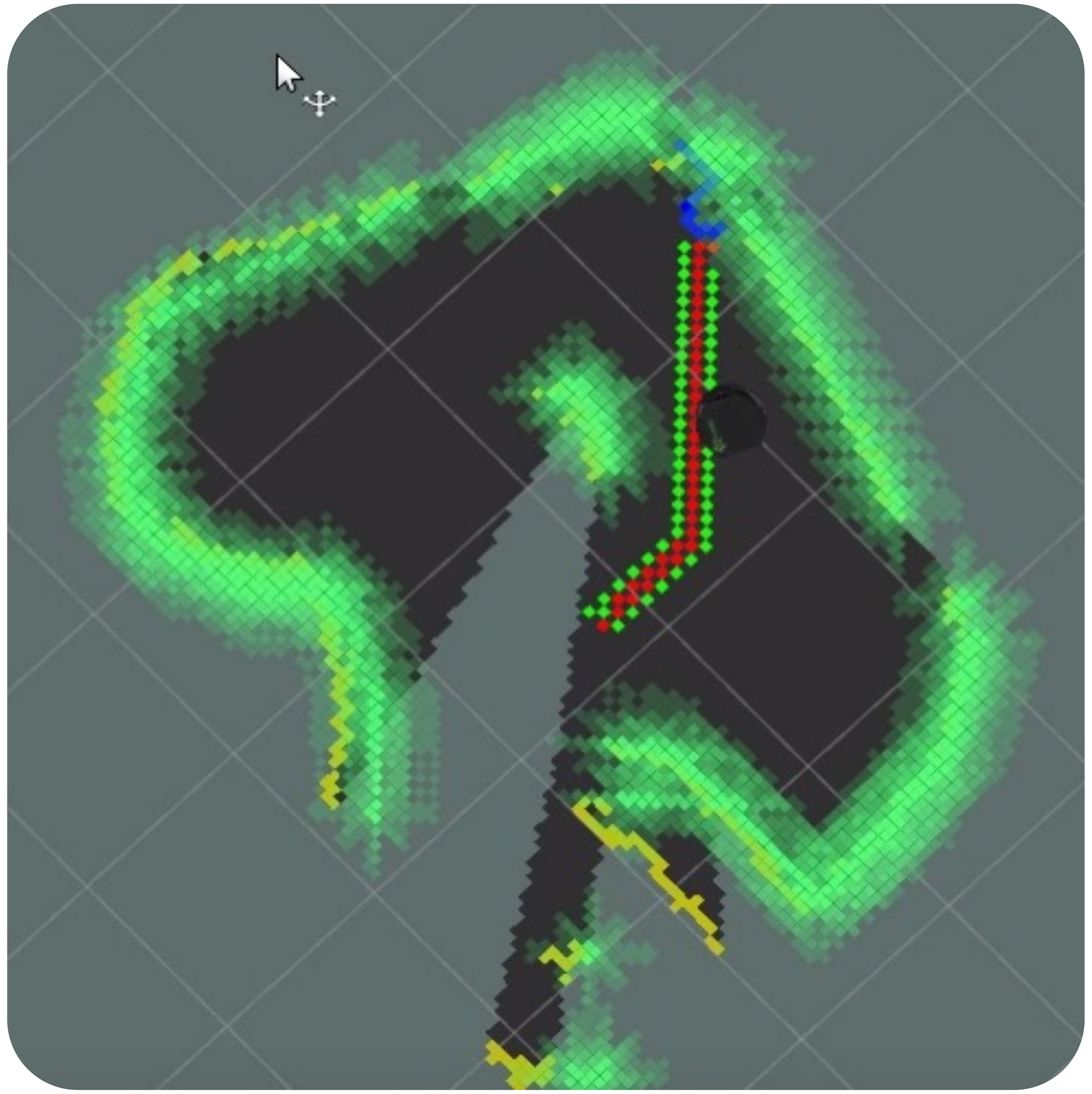
Final Project Leg Landing

RBE 3002 – 2016

Project :
In a 3-Person team we developed exploration algorithm in Python for a Turtlebot robot running ROS. The Robot started in unknown environment and explored unknown frontiers until the entire region was mapped. [Project Writeups]

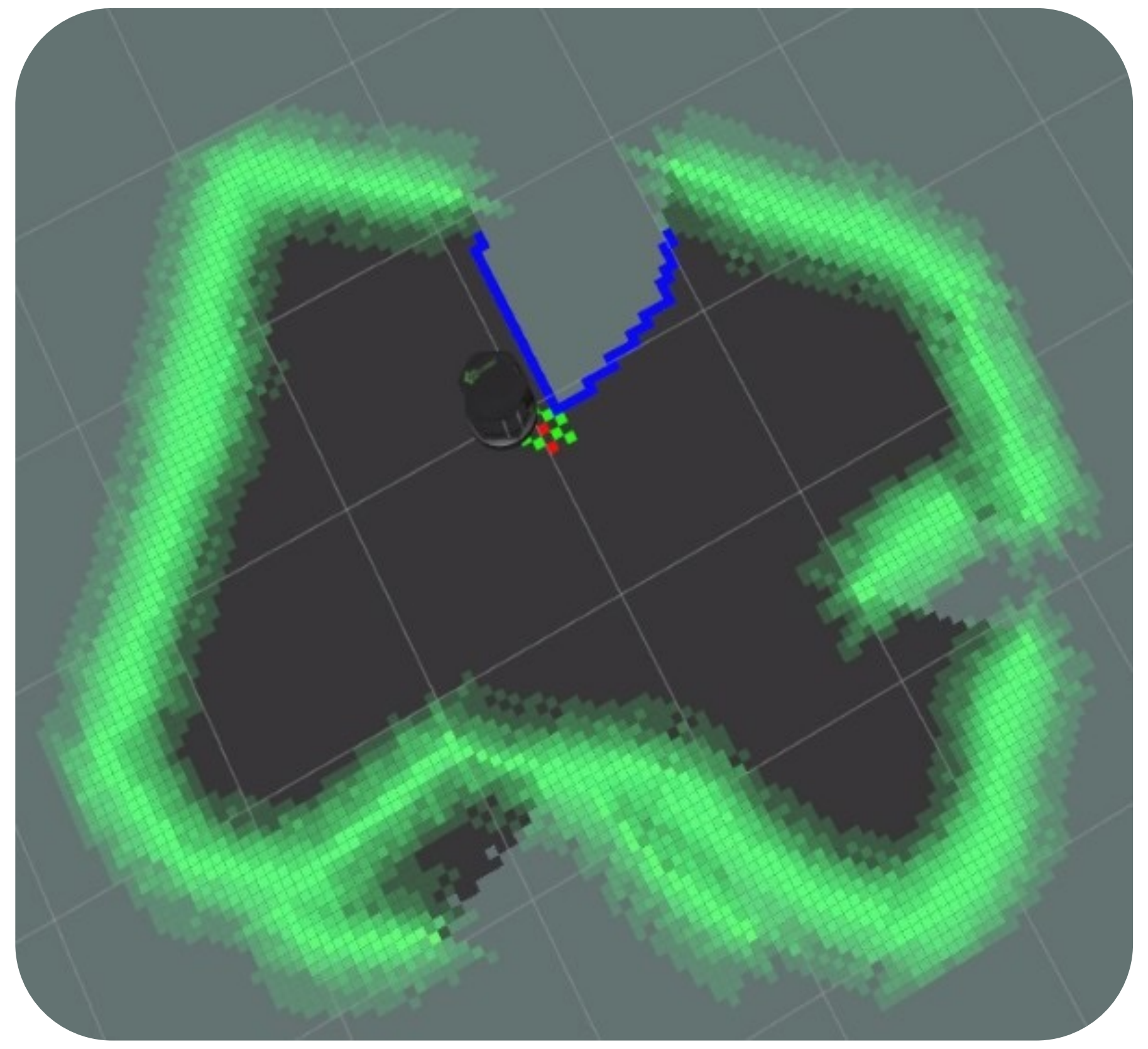
Contribution: I wrote the A* Path planner. To reduce path-planning run time my A* algorithm only expanded diagonally neighboring nodes. This reduced number of expanded nodes by half, required no "map resizing function" and kept the map resolution functionally identical. Run time was cut by more than 50%. Zigzags were filtered out after shortest path determined.

Robot Navigating to Unexplored Region, Planned Path Displayed



Robot in Operation

Robot at Final Unexplored Area

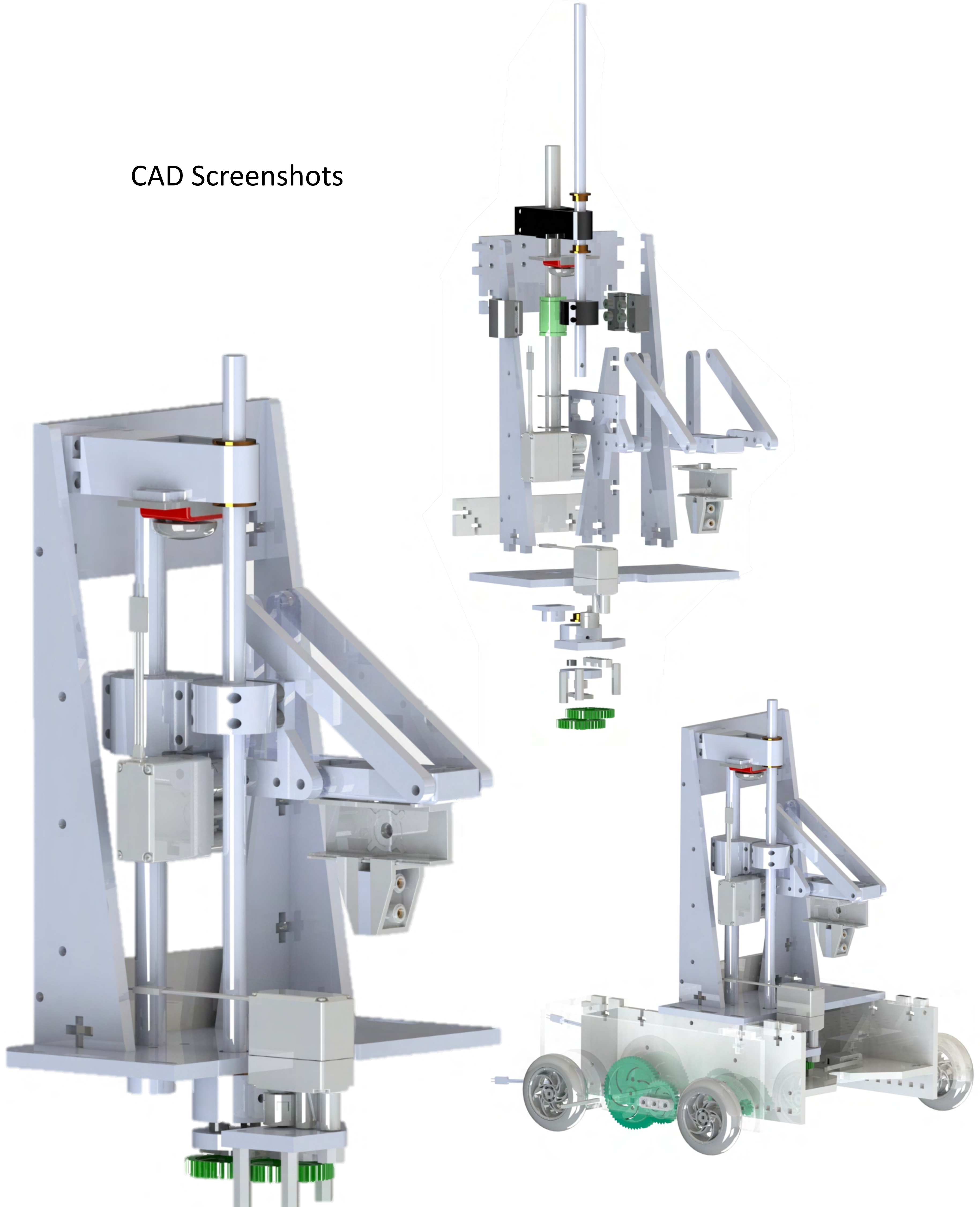


WPI RBE Course 2001 – 2015

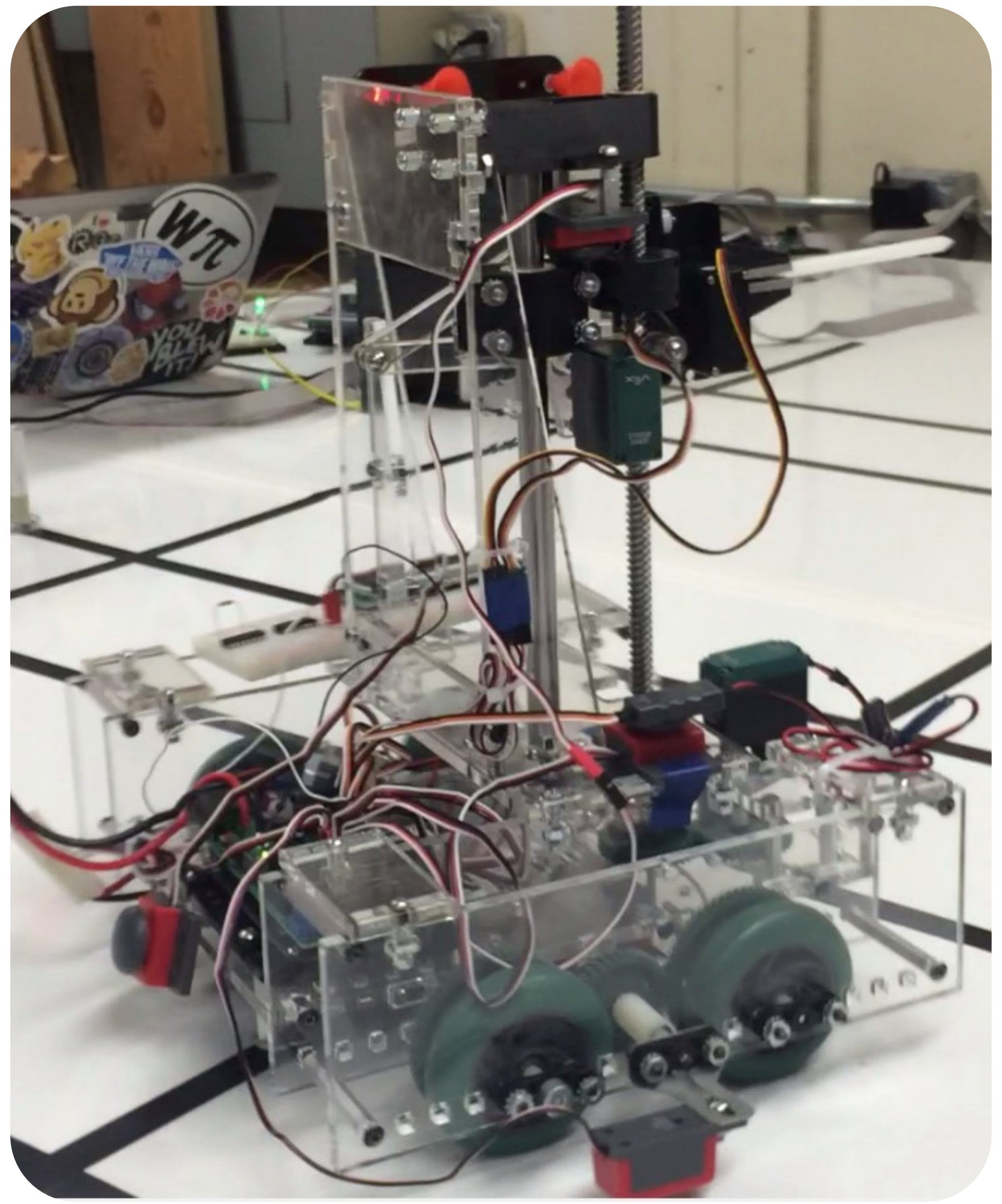
Project :
4 person team had to design and implement a robot that could operate in simulated nuclear facility, picking up "spent fuel rods," placing the rods in horizontal holder, and retrieving and replacing a new fuel rod in "reactor".

Contribution: I designed the rod extraction mechanism.

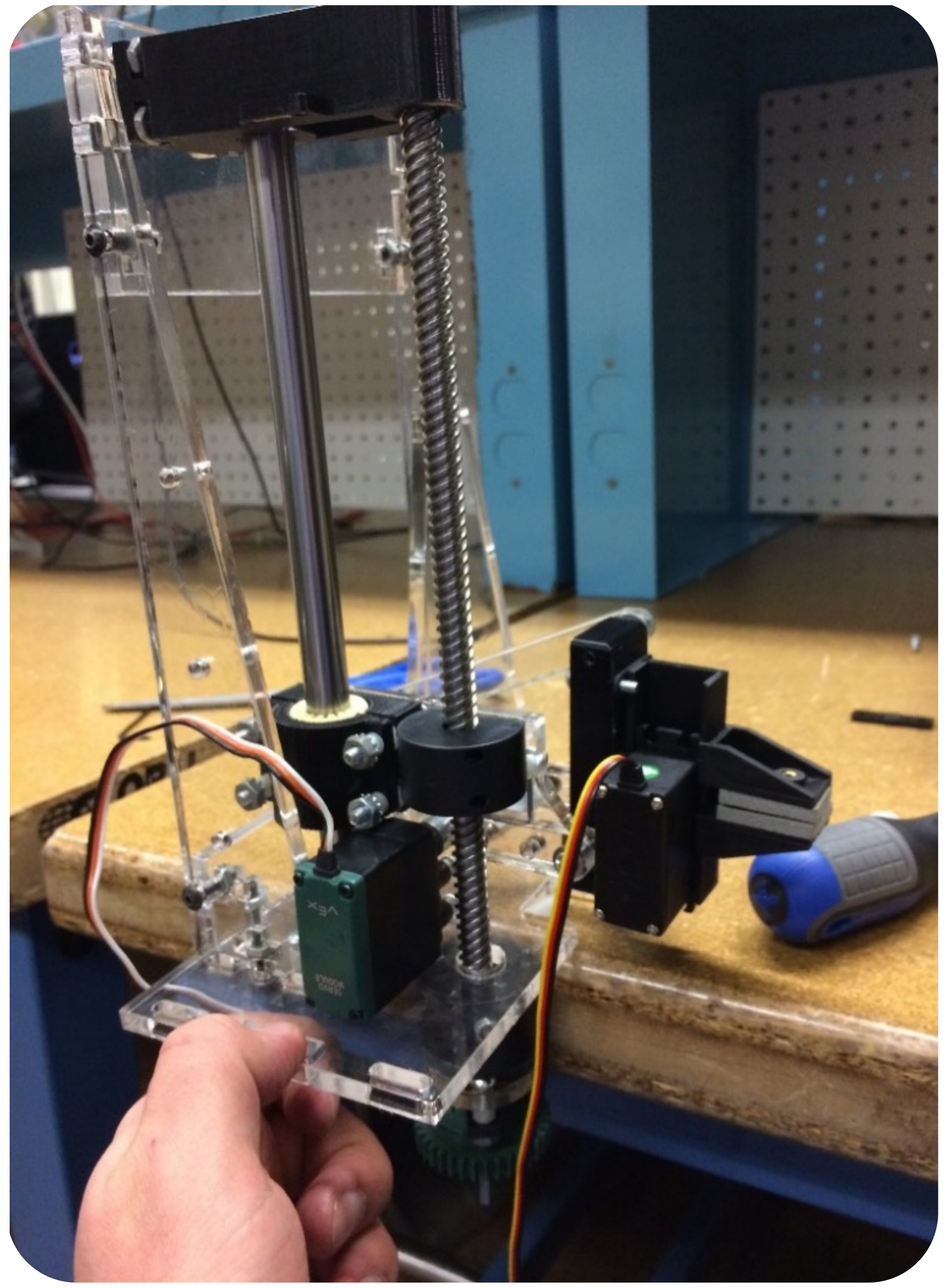
CAD Screenshots



Full Robot



Rod Extraction Mechanism

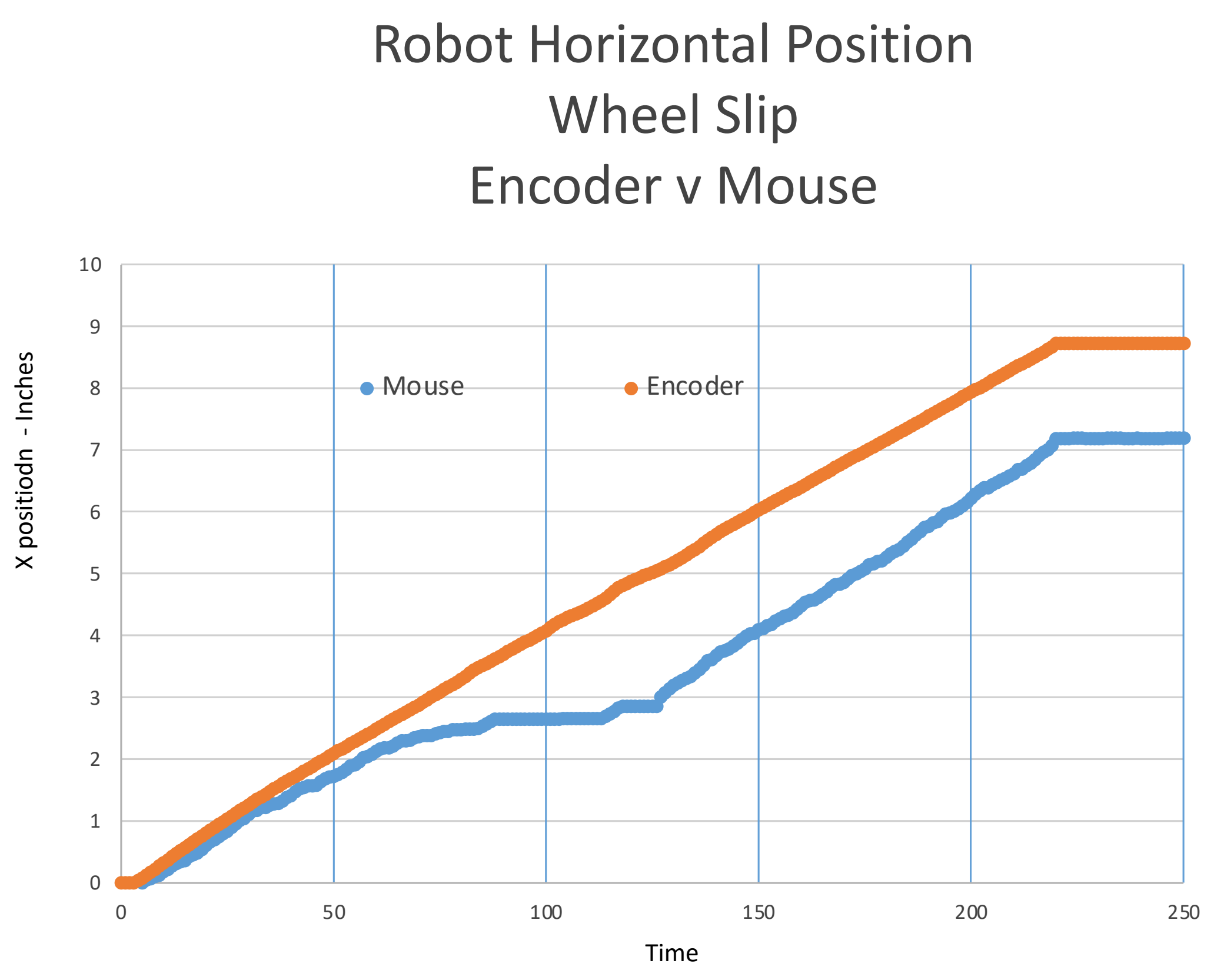


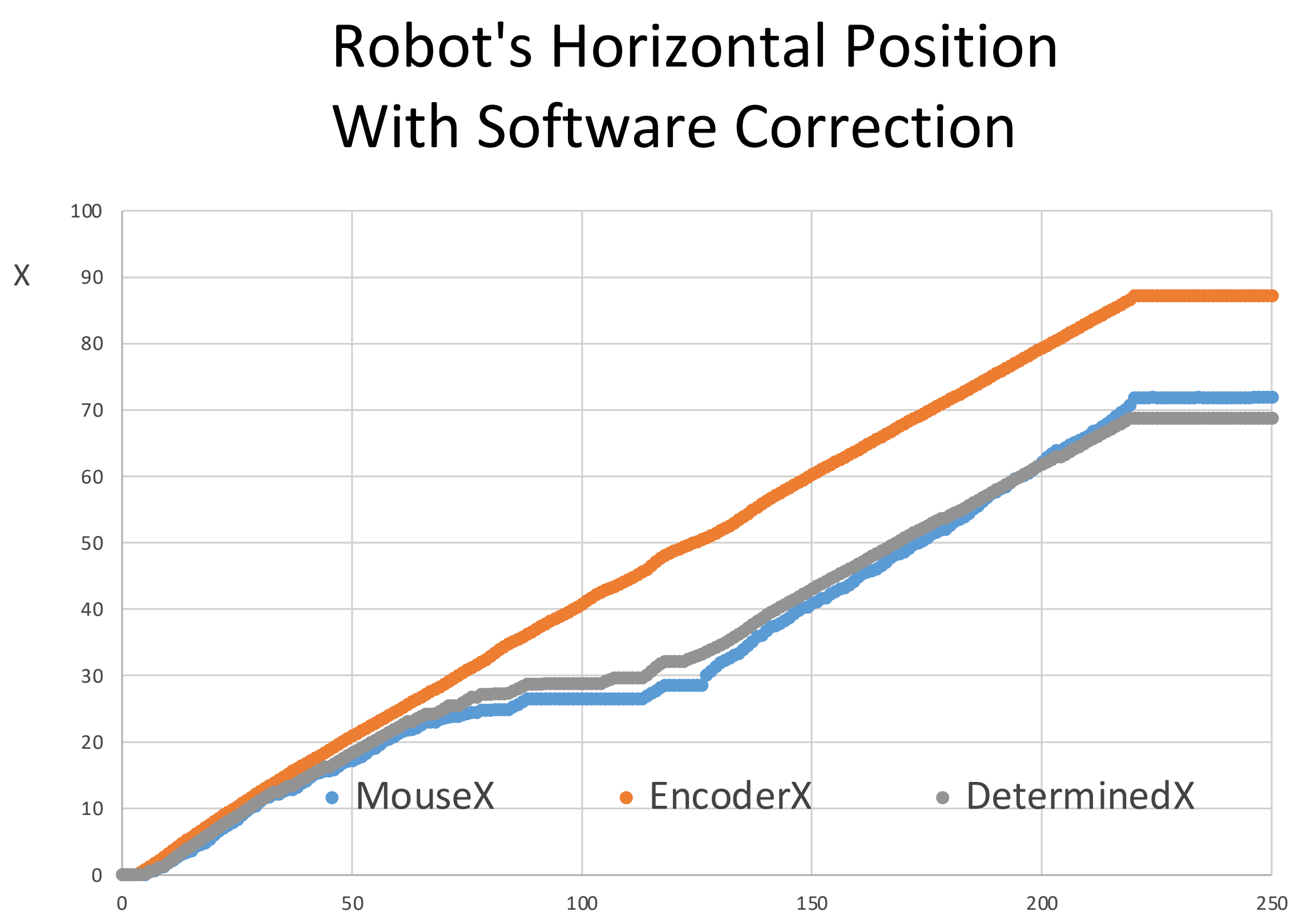
WPI RBE Course 2002 – 2015

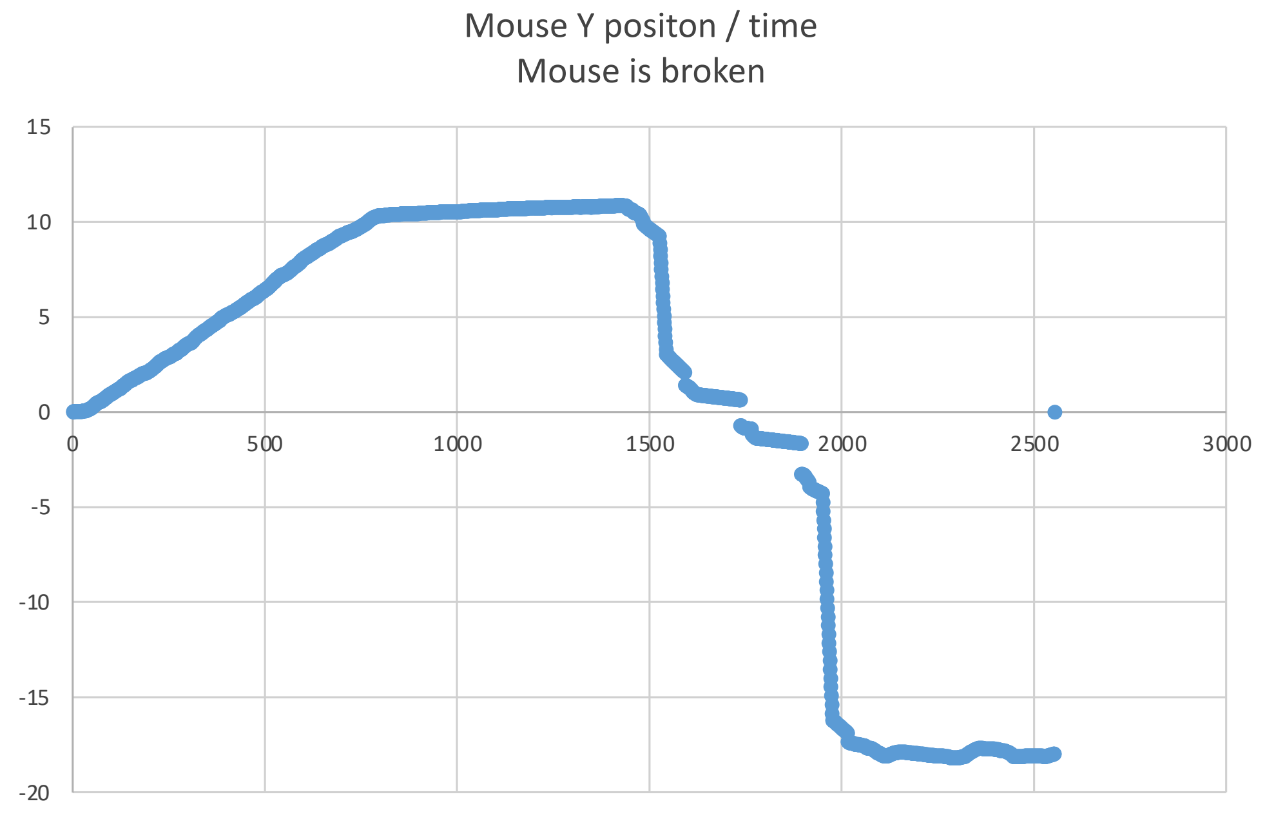
Project :
3-person team was tasked with making a robot to drive around a maze, find a candle, extinguish the flame, and report the location the flame.

Contributions: I designed the full Robot assembly and took advantage of the rapid prototyping resources available to us. The robot was manufactured from laser-cut parts and assorted vex components.

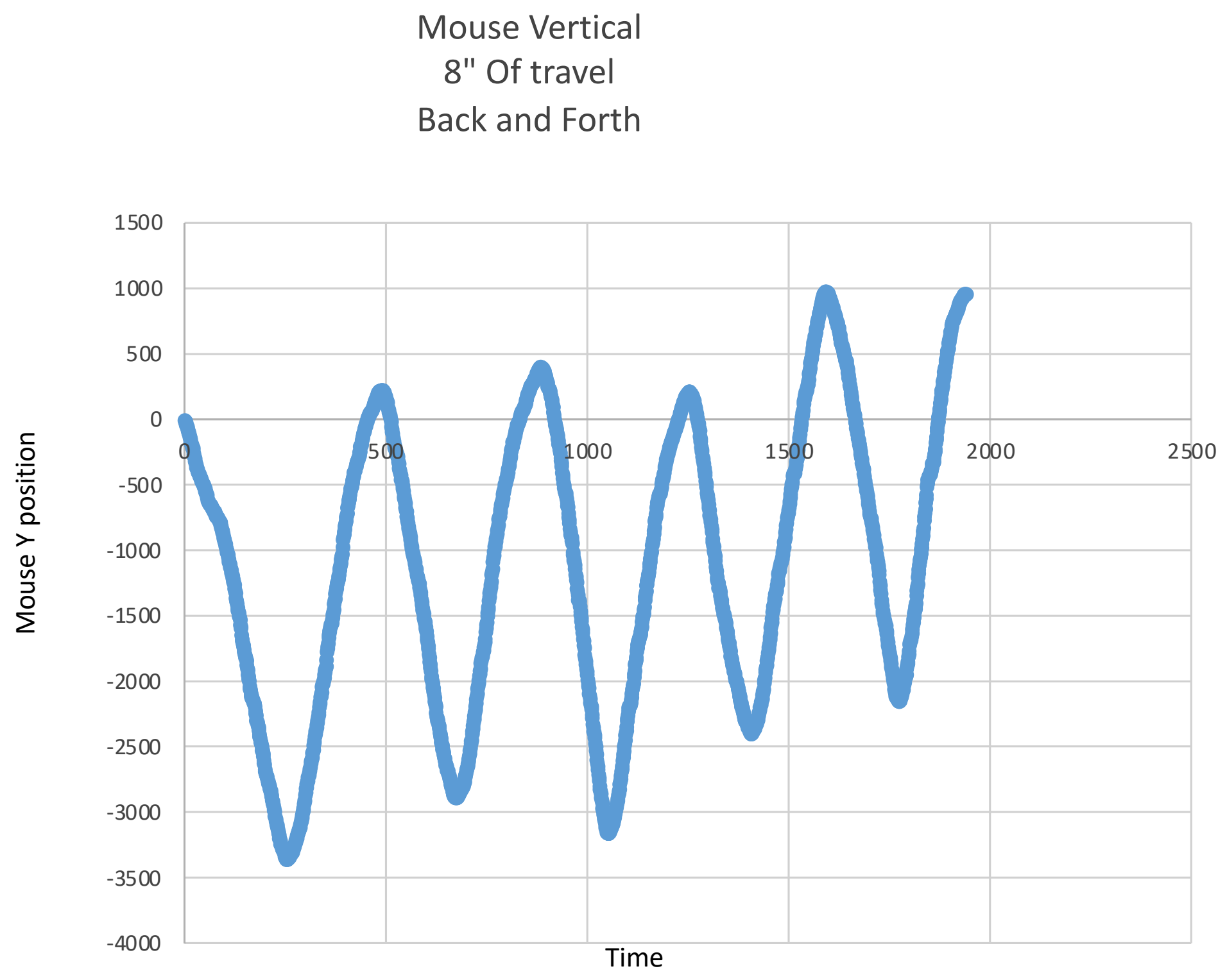
One issue our robot faced was wheels that kept slipping on the whiteboard-surface used as the maze floor. I used a computer mouse to detect when the robot was slipping and compensate for the encoder error. I found that over larger distances the encoder was more reliable than the mouse.

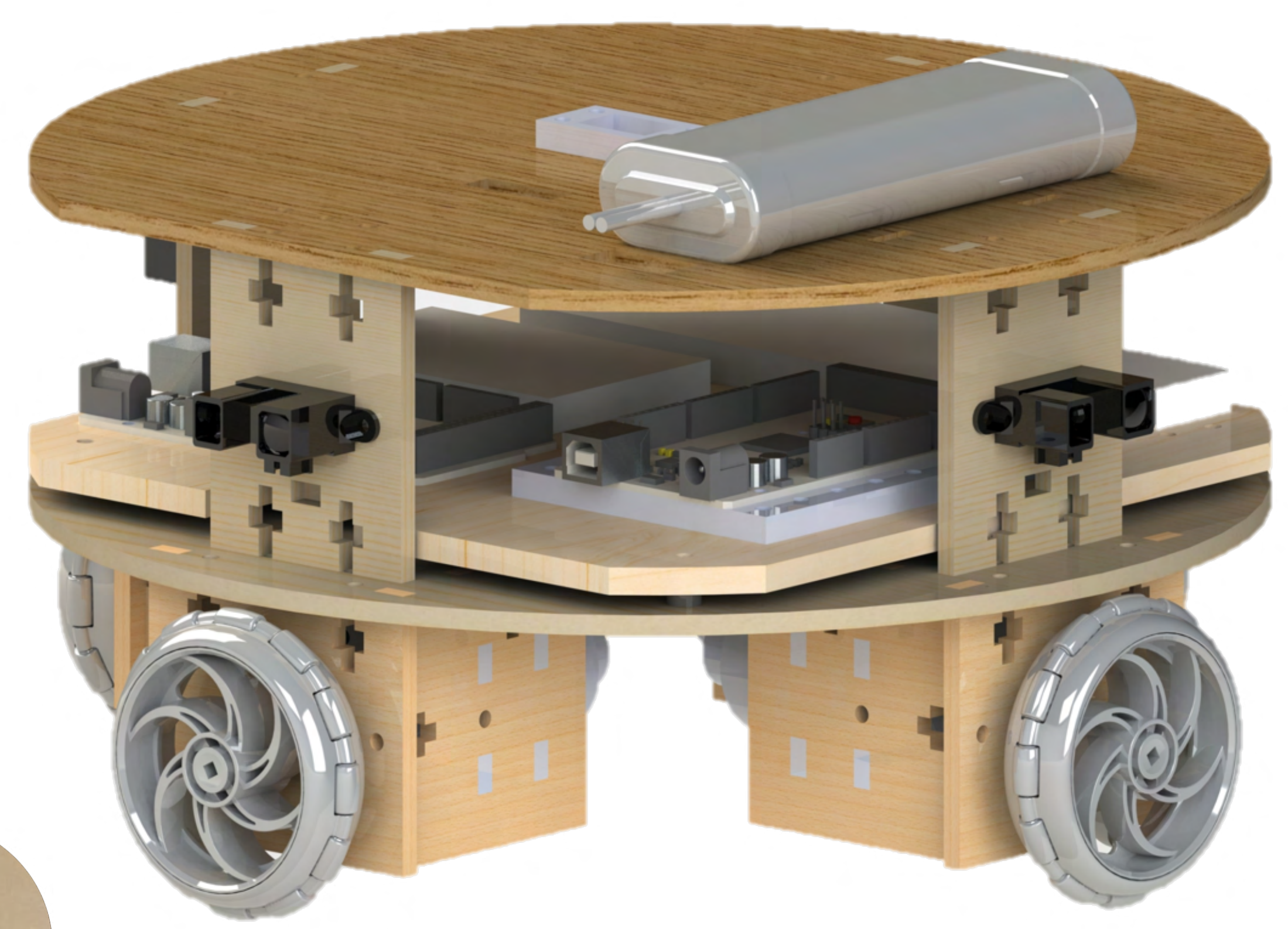


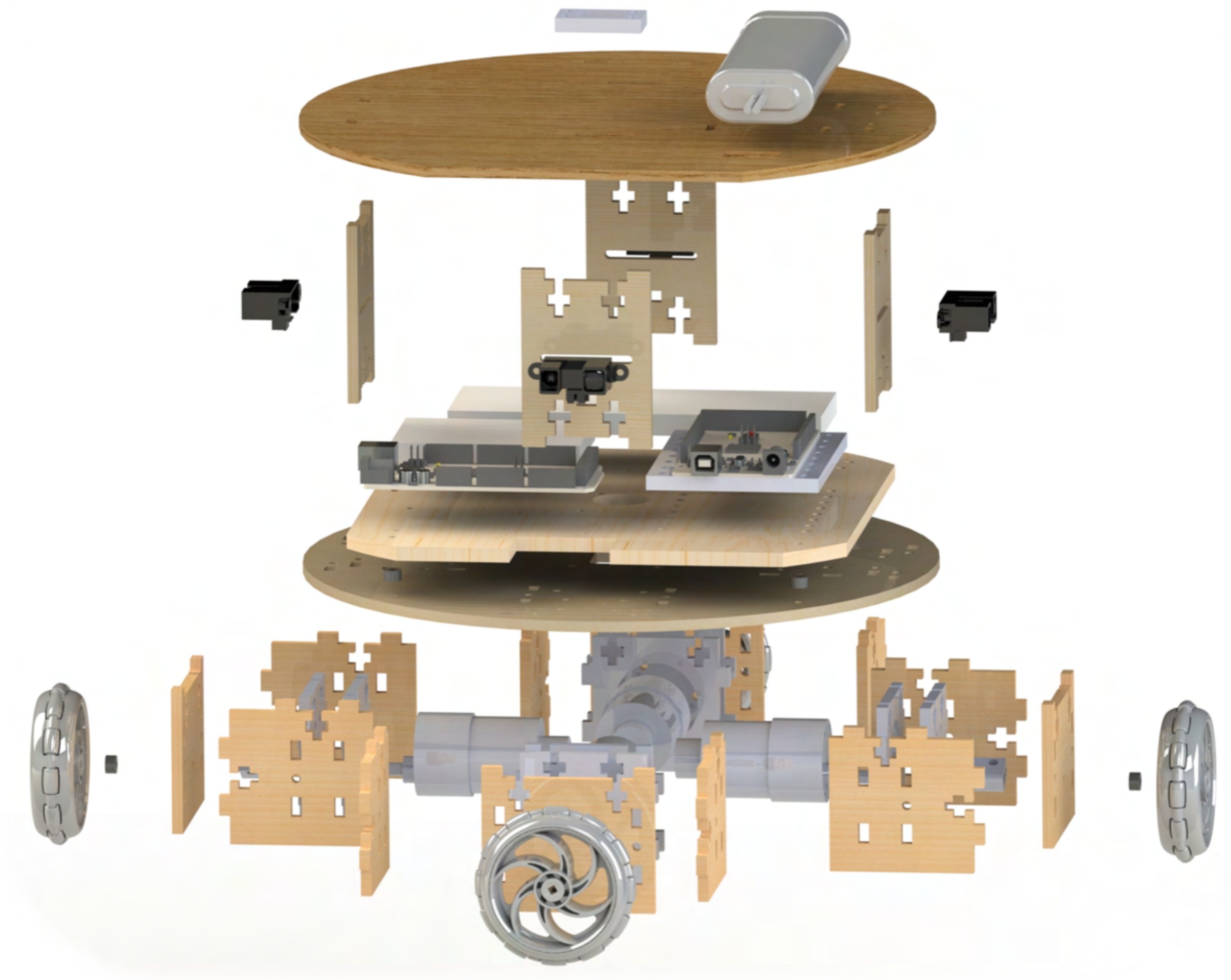


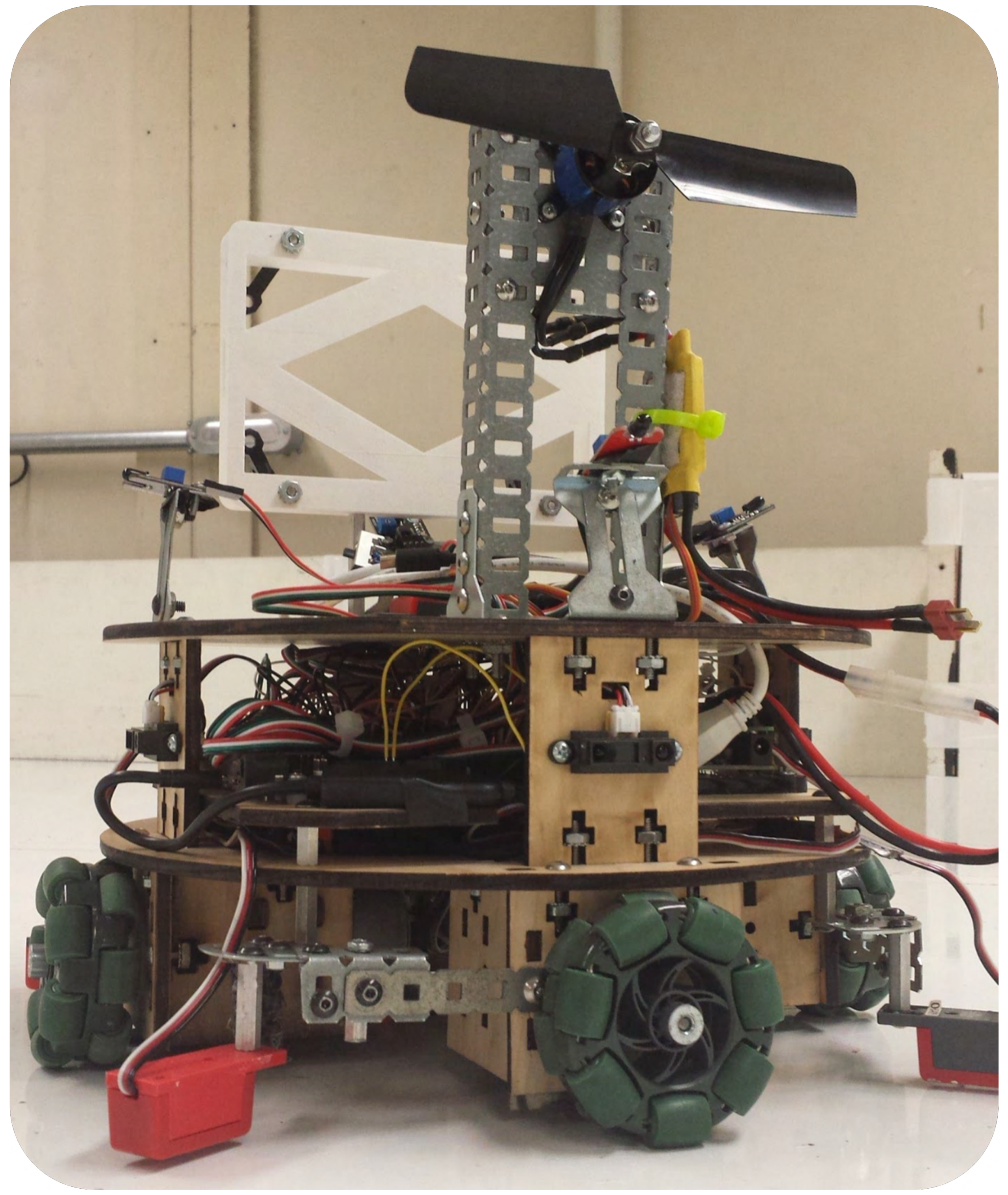


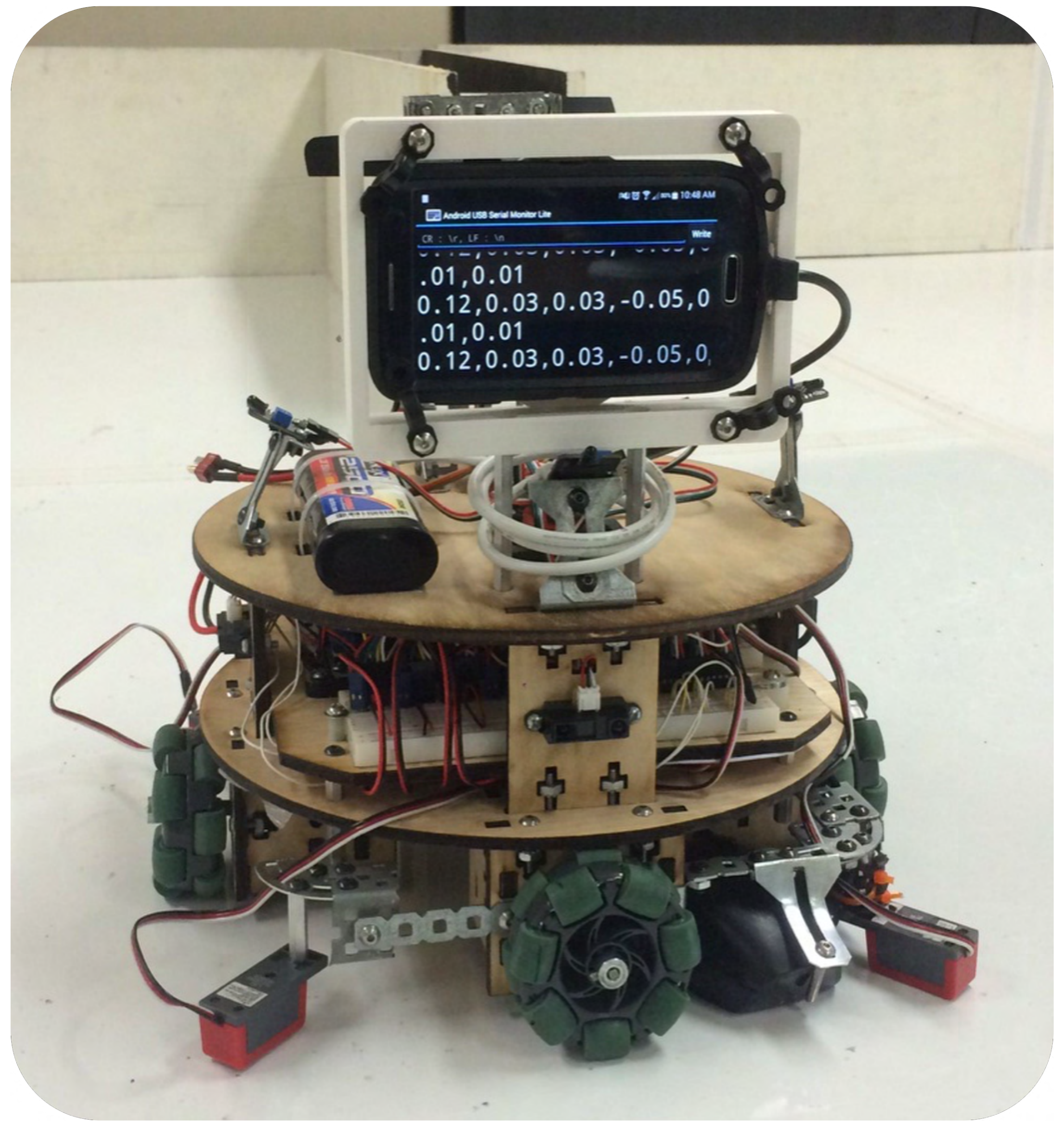
In the testing process I even discovered that my own mouse was broken and needed to be replaced.

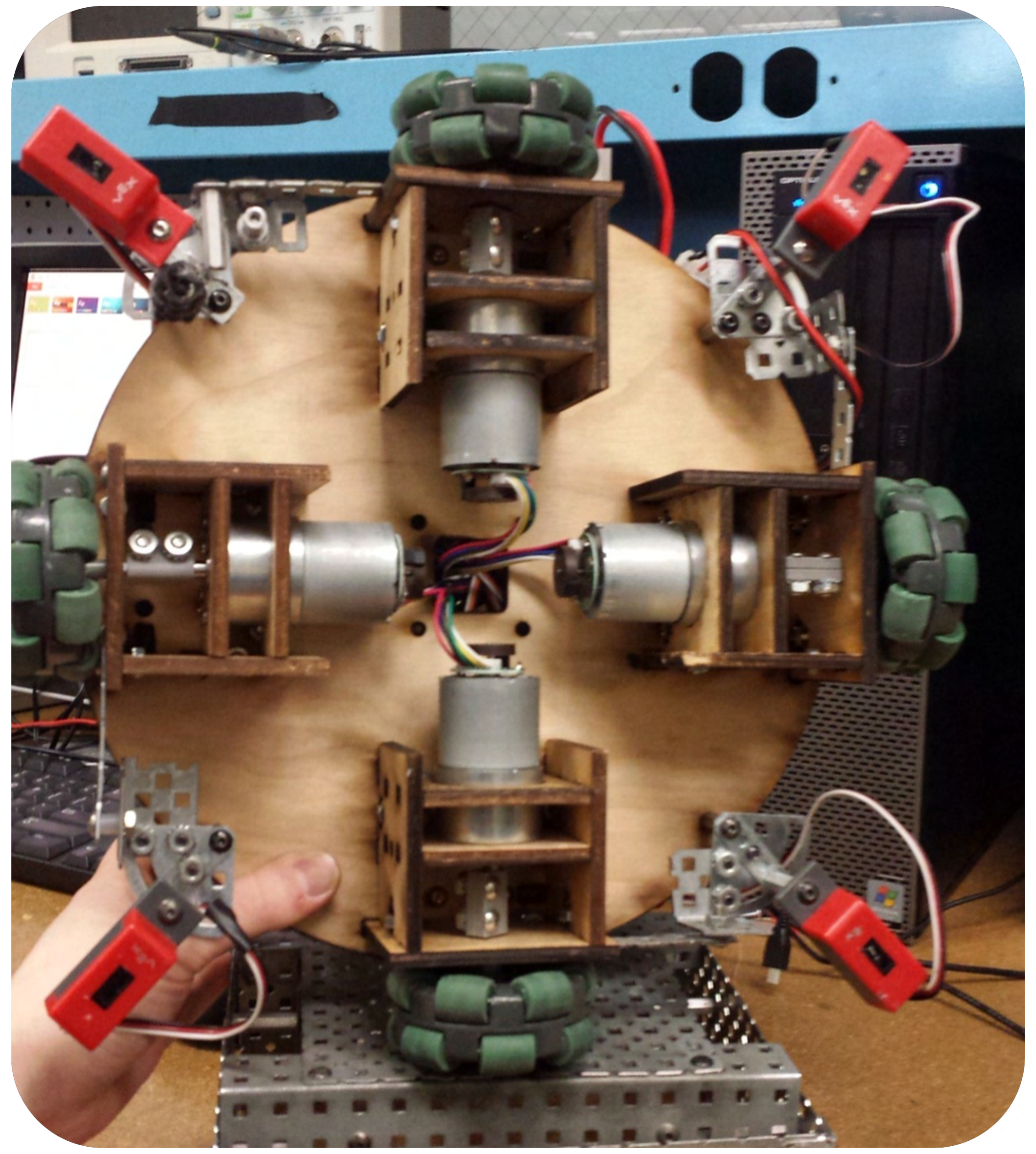












Parts
- 4x Pololu motors for driving
- 4x 3200 count/revolution encoders (1 per wheel)
- 4x SHARP IR sensors, in each cardinal direction
- 4x Flame Sensors
- Brushless DC motor (for fan)
- IR mouse
- Android Smartphone (for Serial Output)

- CAD Design Accounted for Unknown Features:
  - Fan Assembly
  - Function and Characteristics of Flame sensor
  - Size and Mounting Options of Mouse
  - LCD Holder
  - Light Sensors

WPI Course 3733 Software Engineering, Campus Mapping – 2016

Project :

Develop a mapping app for campus that allowed the user to go between any two rooms on different floors and in different buildings. This was a 9-member team that started from scratch to design the mapping app and an app to design the maps all in 4 weeks.

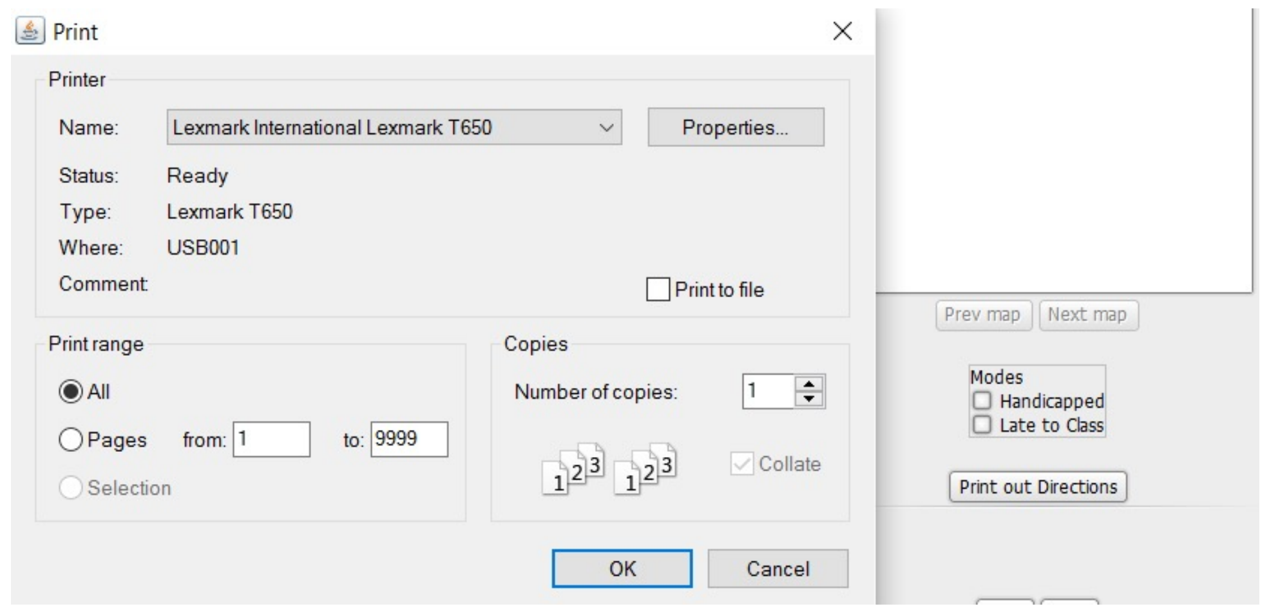
Lessons Learned:

This was an early project in my career which taught me how NOT to run a team. The team culture was toxic, work timeline was ridiculous, and exhausted team members wrote poor code and even worse, pushed changes that broke or overwrote other team members' work. This experience shaped my approach to project management, emphasized the importance of a positive team culture and healthy work habits.

Contributions:

Path smoothing
Human readable directions
Directions export to printer
Testing
Bug fixing
Fixing Git merge conflicts, and
other Git user mistakes

Instructions Printing



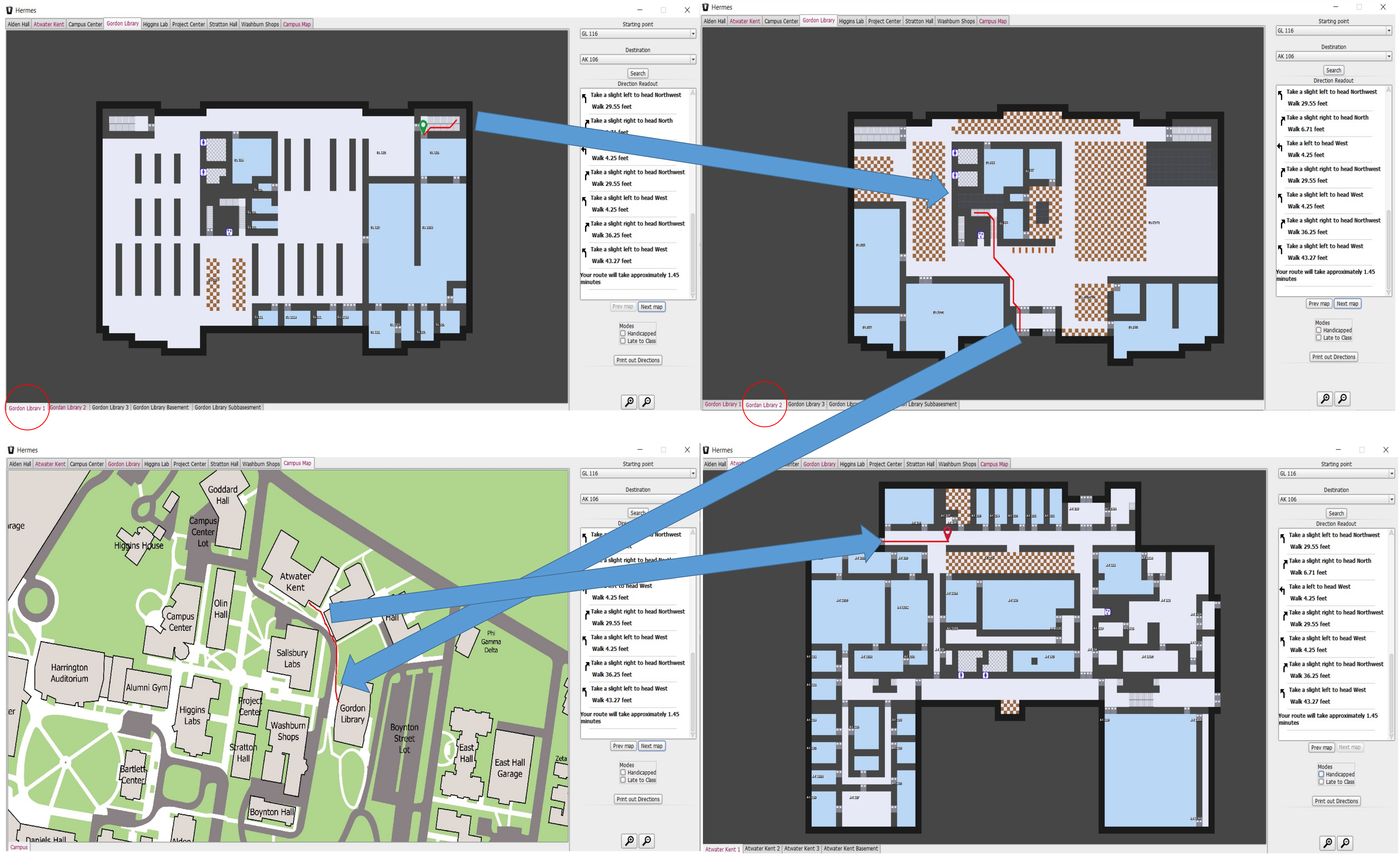
Print

Printer
Name: Lexmark International Lexmark T650
Status: Ready
Type: Lexmark T650
Where: USB001
Comment:
☐ Print to file

Print range
● All
○ Pages from: 1 to: 9999
○ Selection

Copies
Number of copies: 1
☑ Collate

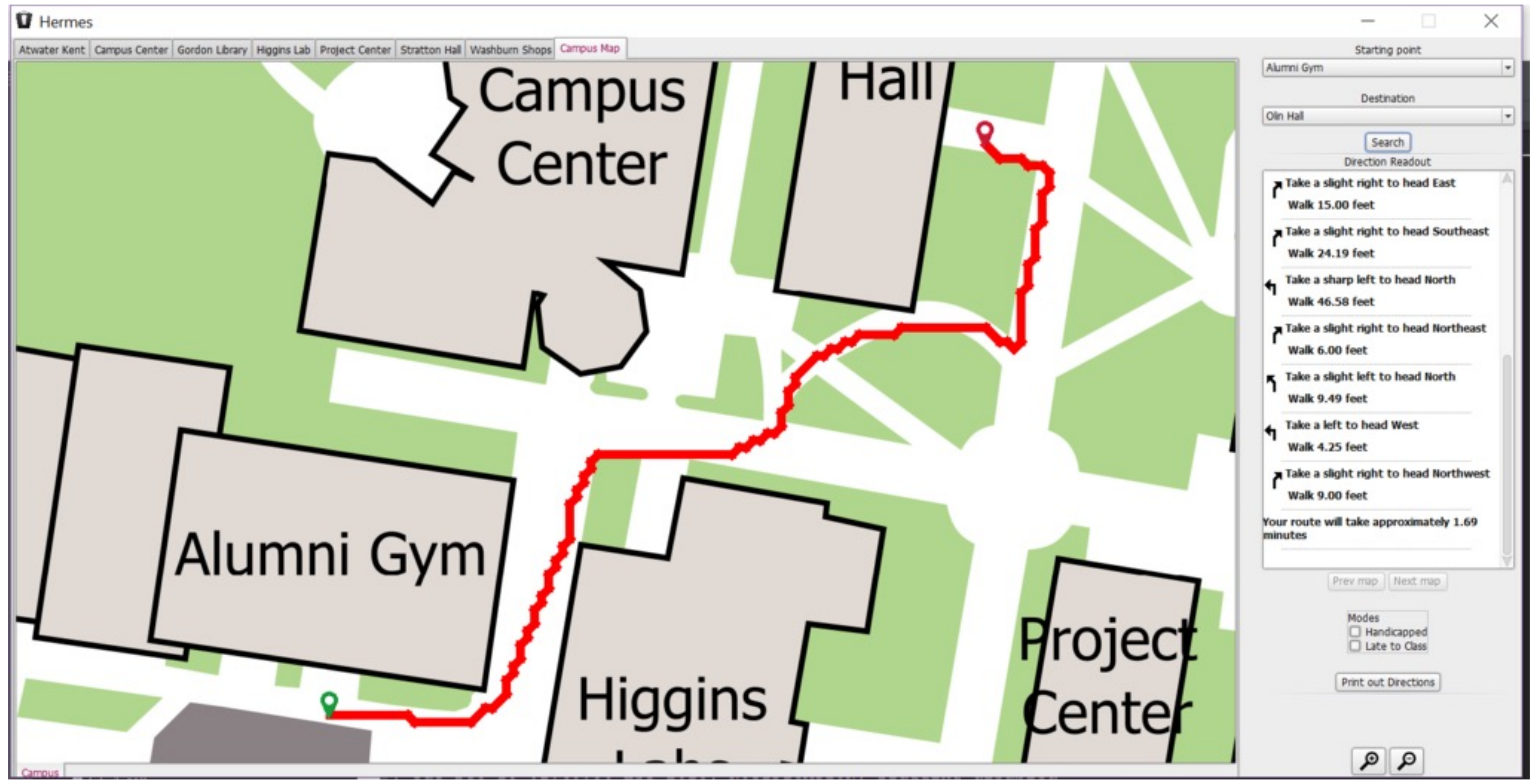
Planned Path from Between Buildings



Starting point: GL 116
Destination: AK 106

Direction Readout
Take a slight left to head Northwest
Walk 29.55 feet
Take a slight right to head North
Walk 6.71 feet
Take a left to head West
Walk 4.25 feet
Take a slight right to head Northwest
Walk 29.55 feet
Take a slight left to head West
Walk 4.25 feet
Take a slight right to head Northwest
Walk 36.25 feet
Take a slight left to head West
Walk 43.27 feet
Your route will take approximately 1.45 minutes

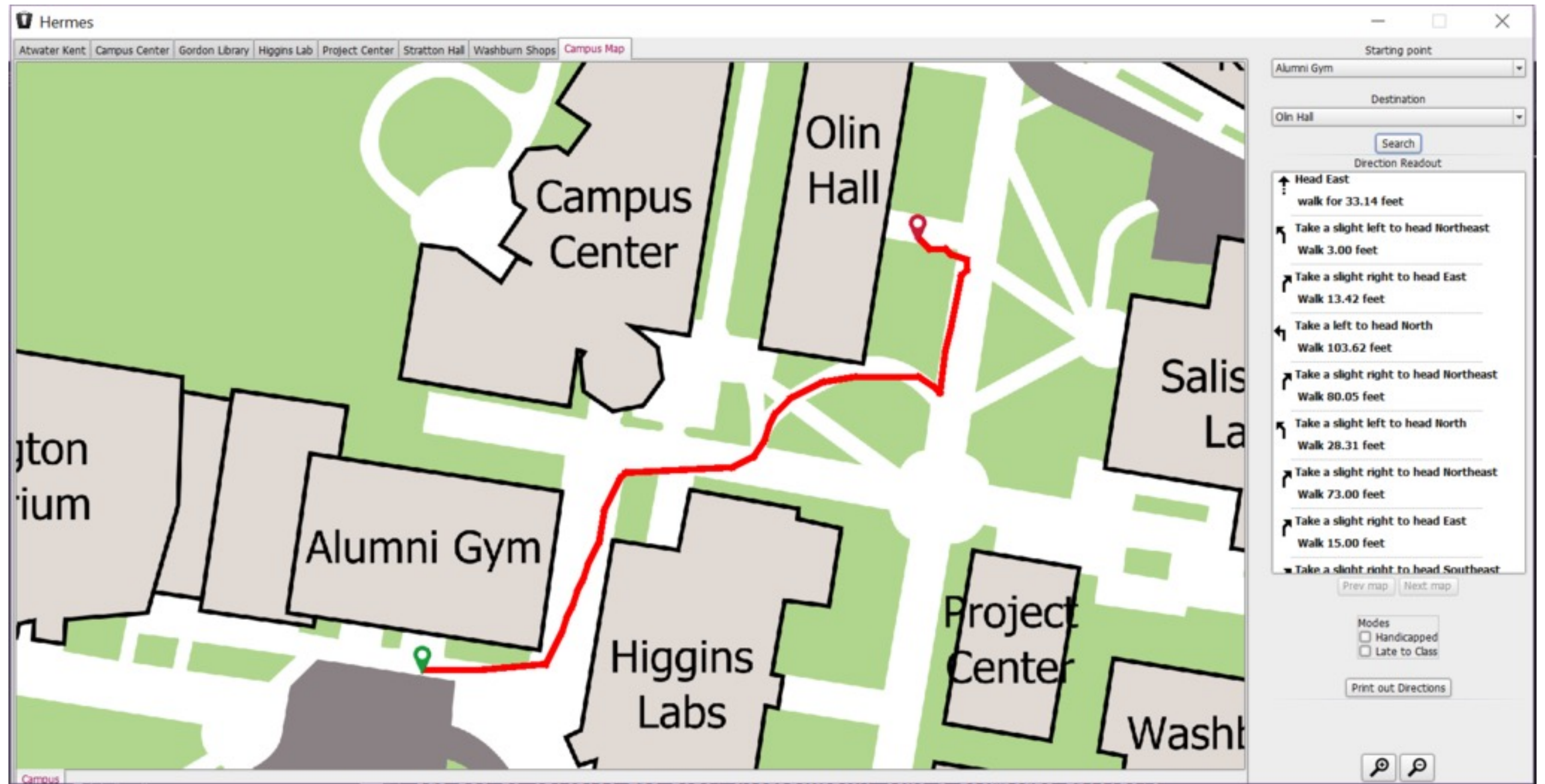
Pre-Smoothed Path



Starting point: Alumni Gym
Destination: Olin Hall

Direction Readout
Take a slight right to head East
Walk 15.00 feet
Take a slight right to head Southeast
Walk 24.19 feet
Take a sharp left to head North
Walk 46.58 feet
Take a slight right to head Northeast
Walk 6.00 feet
Take a slight left to head North
Walk 9.49 feet
Take a left to head West
Walk 4.25 feet
Take a slight right to head Northwest
Walk 9.00 feet
Your route will take approximately 1.69 minutes

Smoothed Path



Starting point: Alumni Gym
Destination: Olin Hall

Direction Readout
Head East
walk for 33.14 feet
Take a slight left to head Northeast
Walk 3.00 feet
Take a slight right to head East
Walk 13.42 feet
Take a left to head North
Walk 103.62 feet
Take a slight right to head Northeast
Walk 80.05 feet
Take a slight left to head North
Walk 28.31 feet
Take a slight right to head Northeast
Walk 73.00 feet
Take a slight right to head East
Walk 15.00 feet
Take a slight right to head Southeast