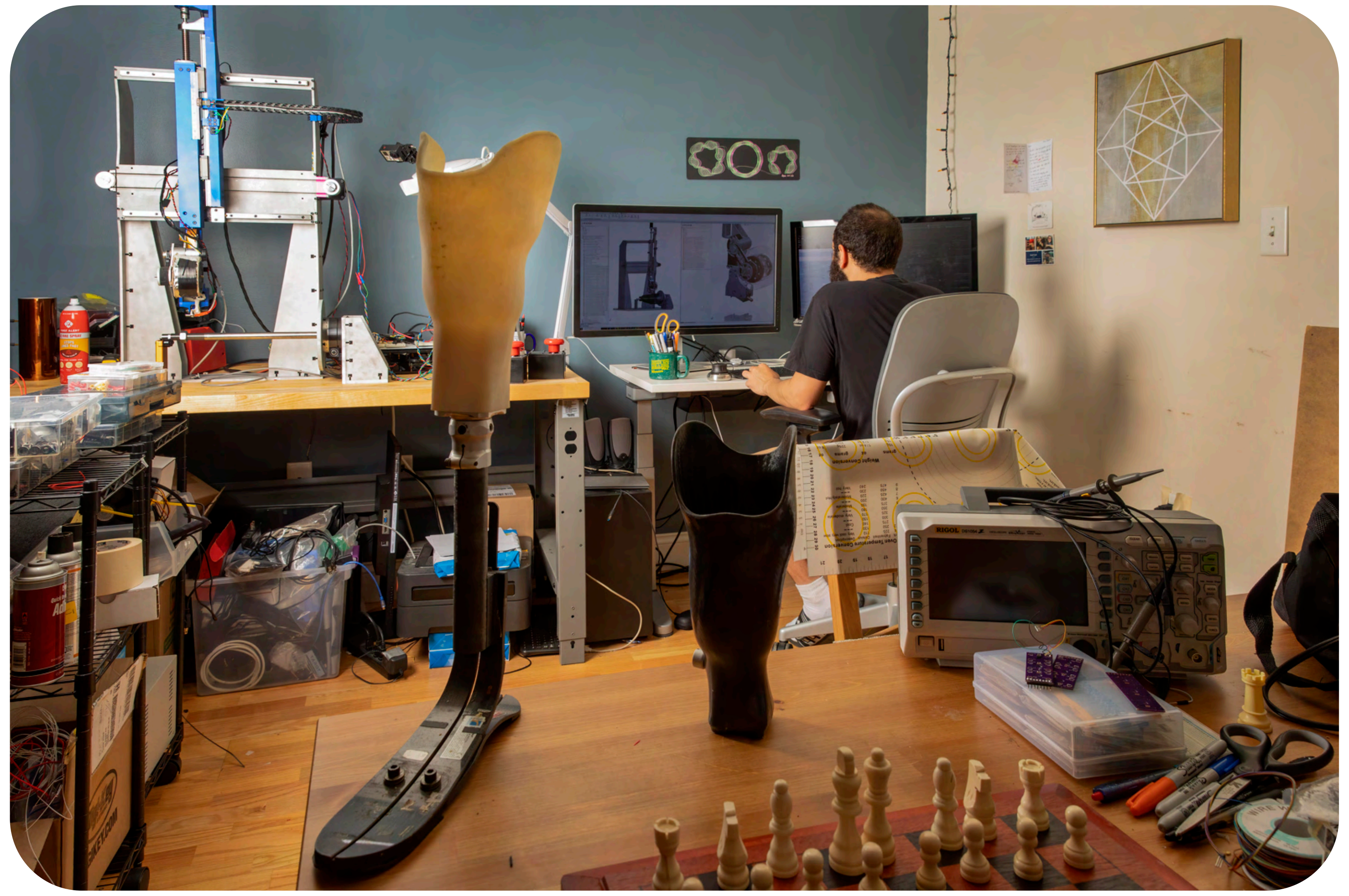
Master’s Thesis - 2019-2021: Prosthetic Socket Fabrication

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.

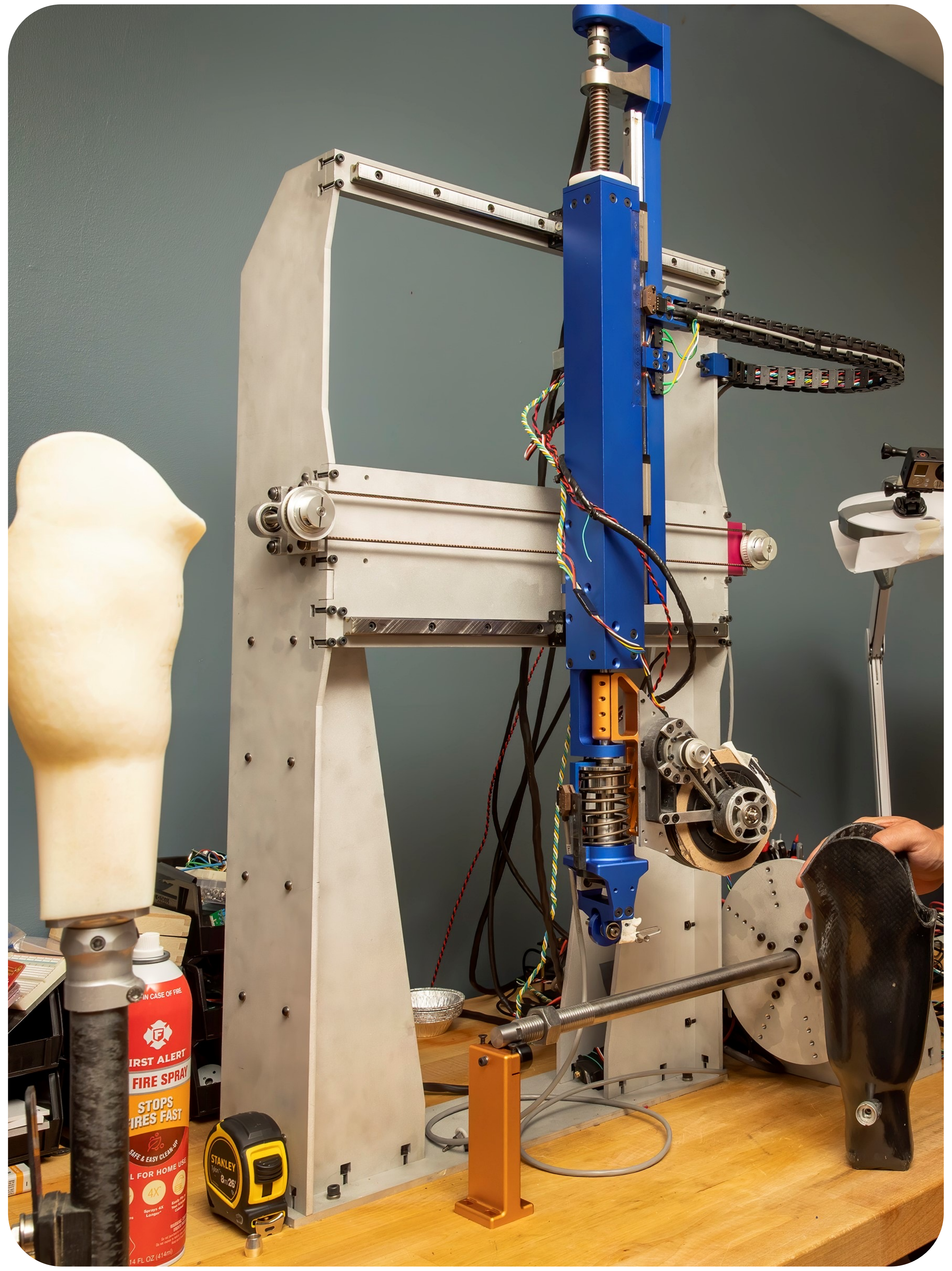
Project Type:
Thesis project. Independently to identified a problem, proposed a solution, then defined, analyzed, designed, built, programmed, tested, and evaluated the system.



Remote Media Lab Setup

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

The Desktop AFP Prototype



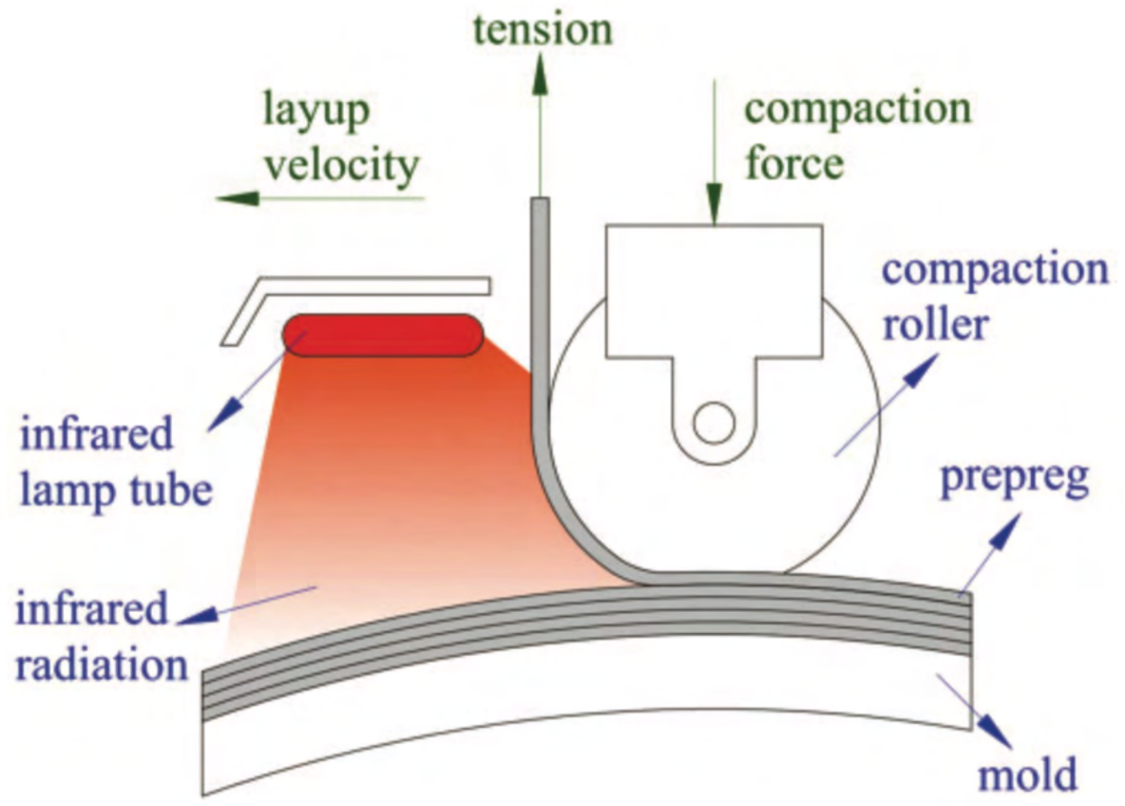
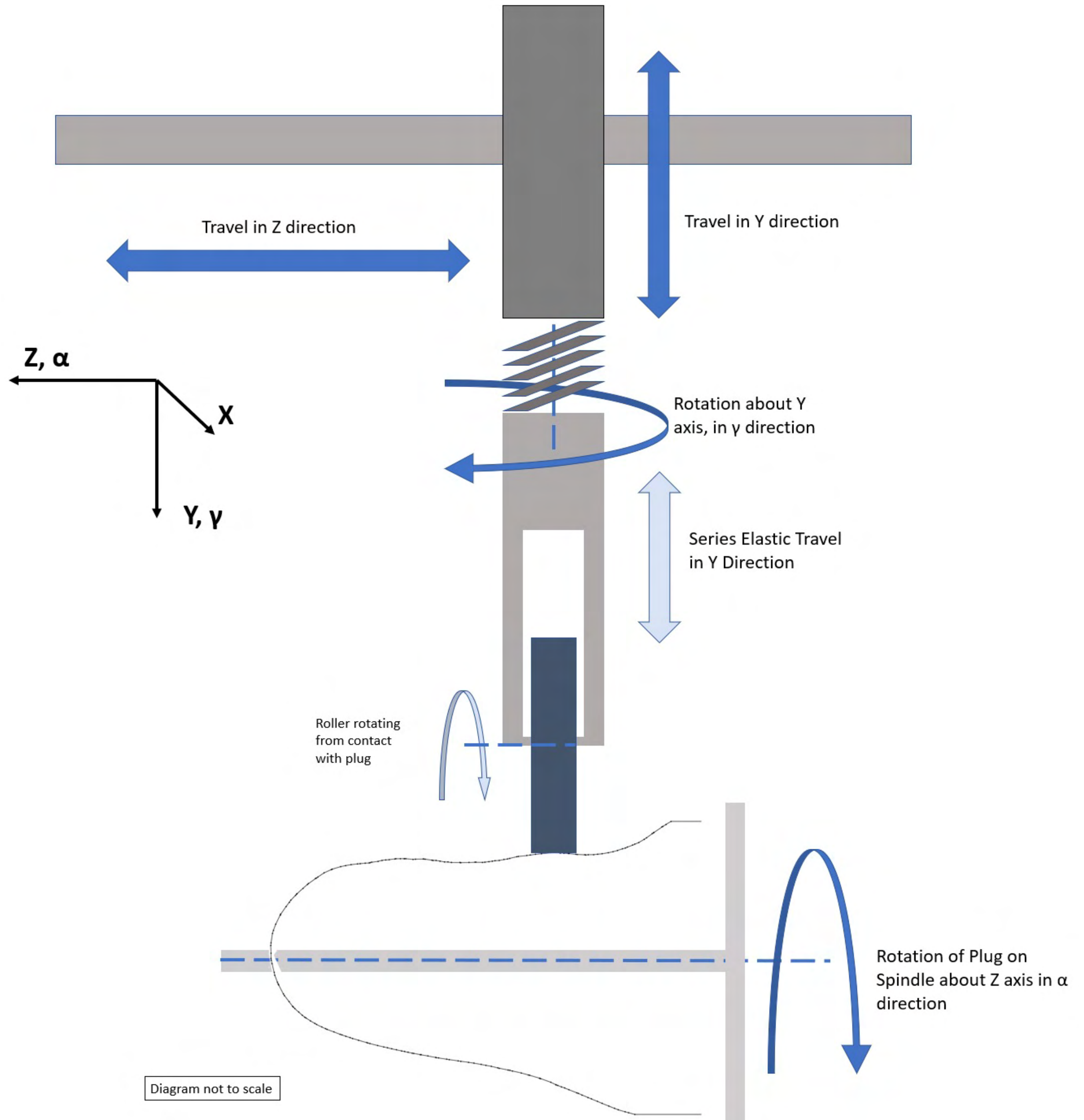


Figure 1. The automated fiber placement (AFP) process.

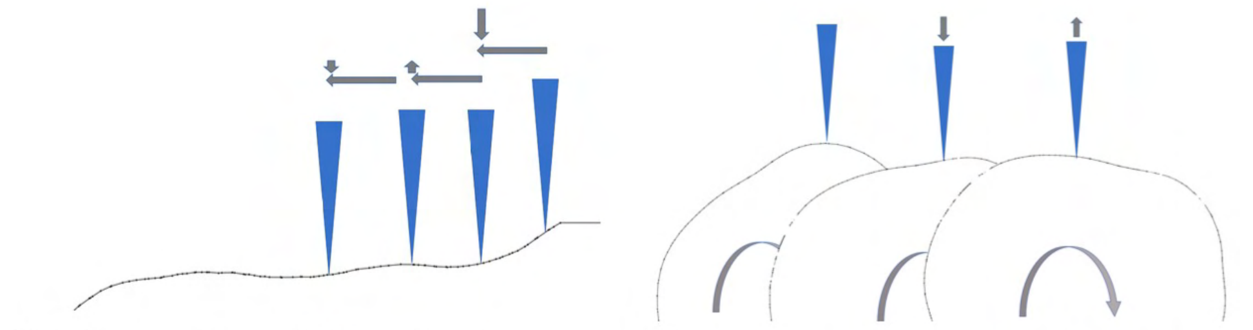
Jiang, J., He, Y., & Ke, Y. (2019). Pressure distribution for automated fiber placement and design optimization of compaction rollers. Journal of Reinforced Plastics and Composites, 38(18), 860–870. https://doi.org/10.1177/0731684419850896

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

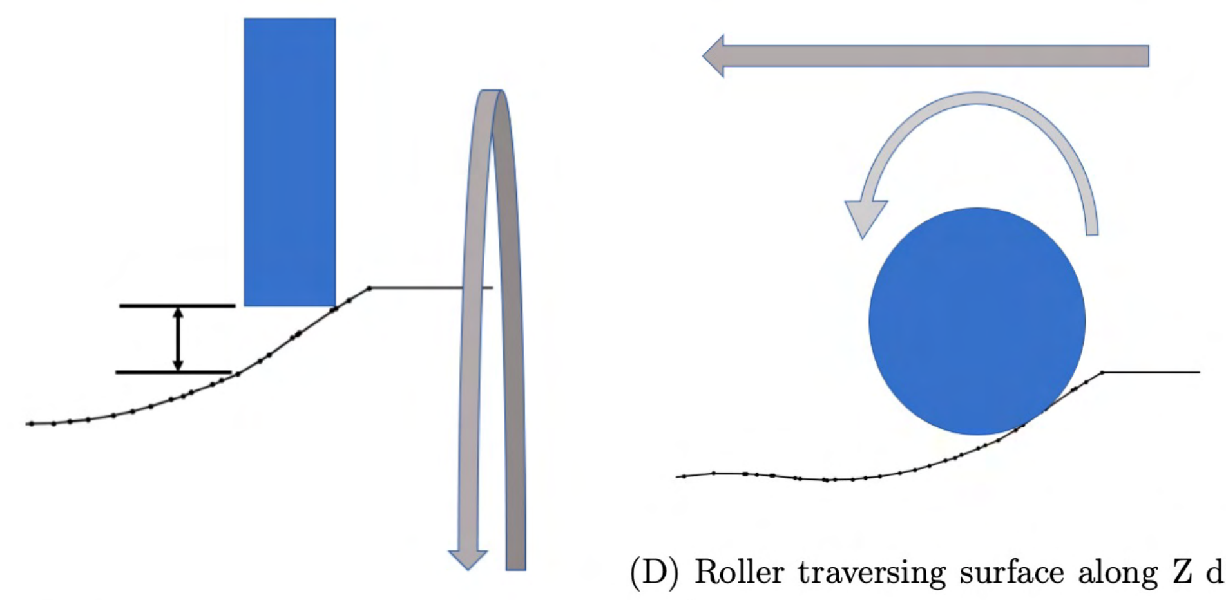


Degrees of Freedom Necessary to Traverse the Socket Geometry



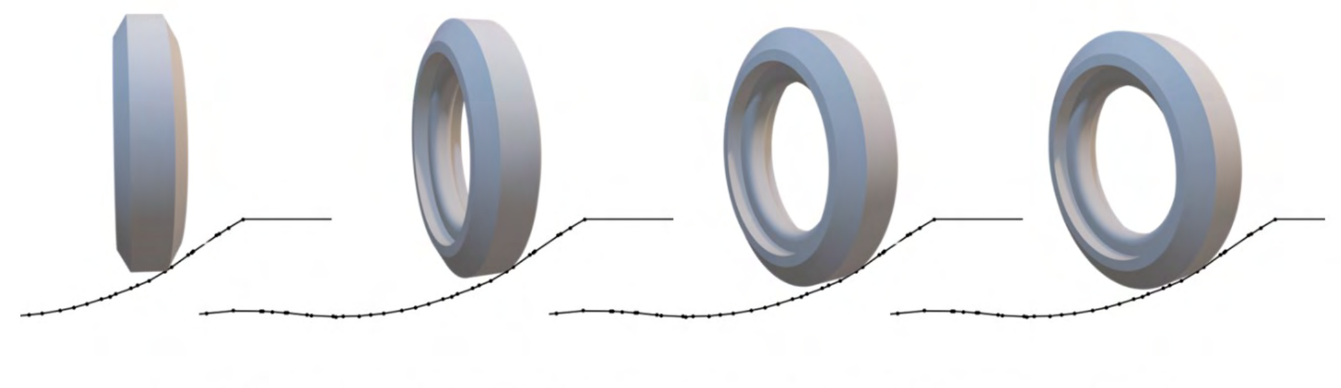
(A) Socket traversal along the Z axis. Requires motion in Z and Y direction

(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

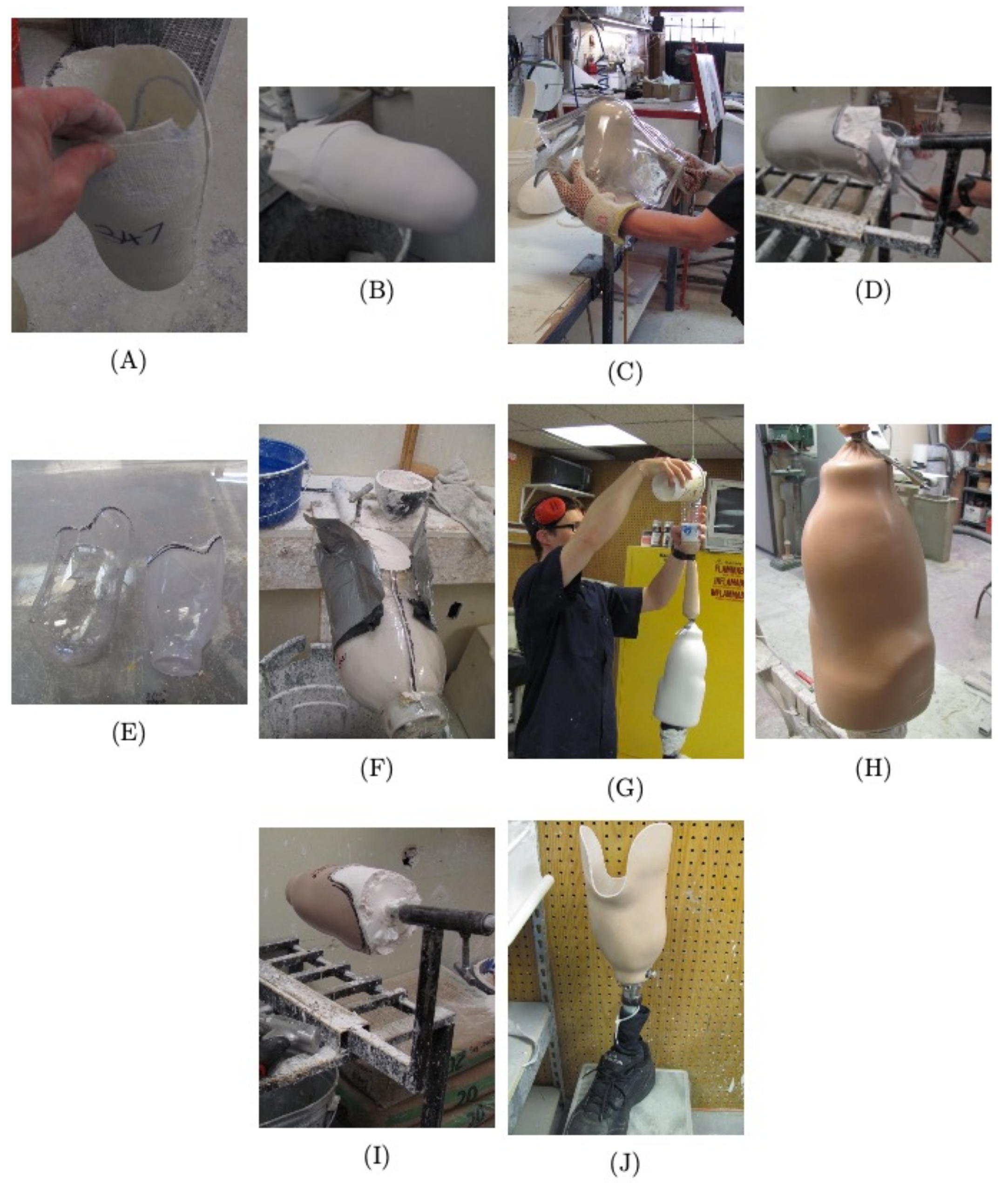


Figure 1-2: The abbreviated socket building process. A) Cast of wearer. B) Positive plaster mold. (C) Forming a temporary check socket. D) Destroying the original mold. E) The plastic check socket. F) Filling the check socket with plaster, and cutting the check socket in half to free the mold. G) Pouring 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

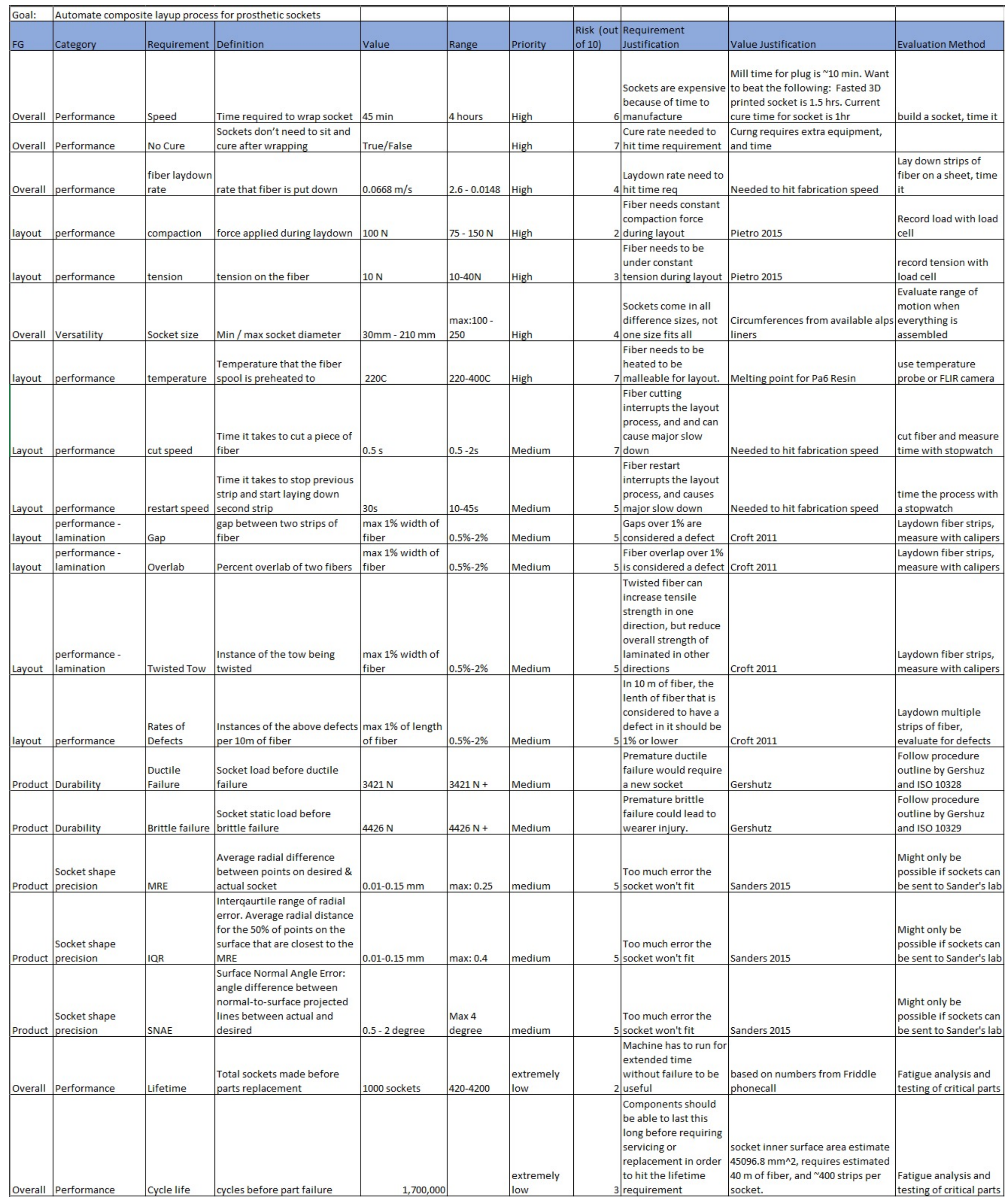
Analysis
- Determine AFP Functional Requirements
- Develop personal python modeling toolbox
- Calculate machine and component performance

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)

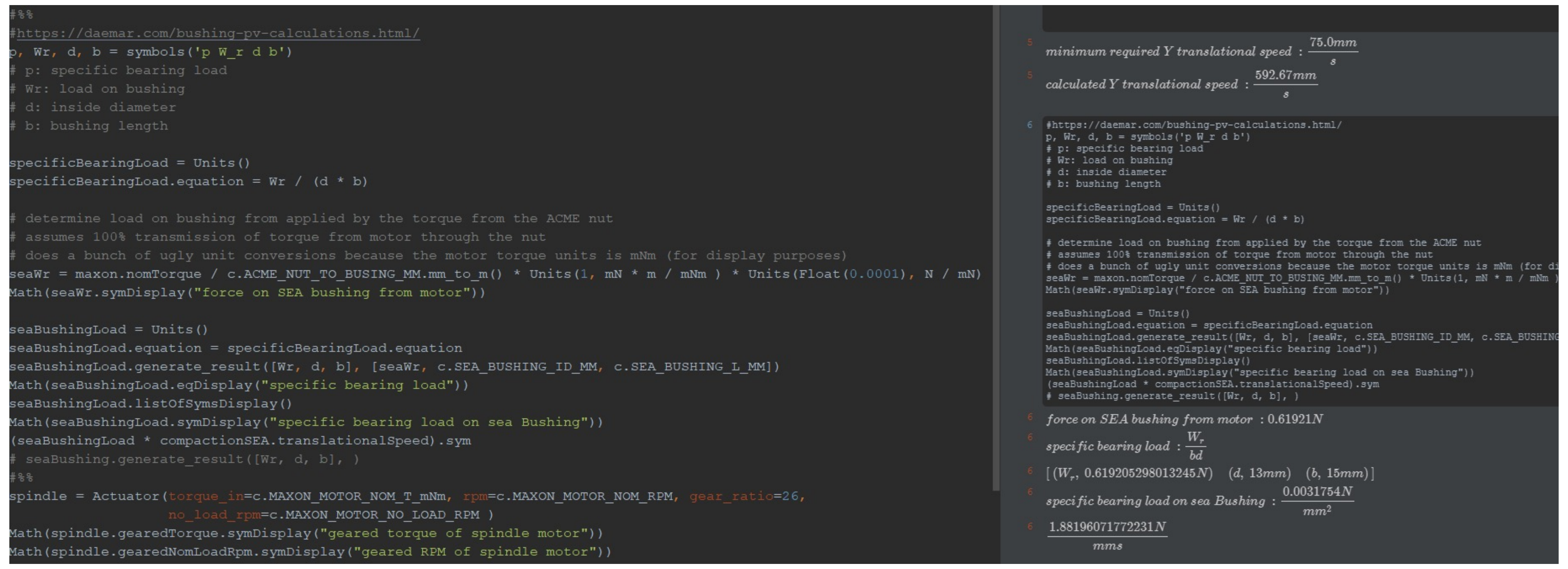


Goal: Automate composite layup process for prosthetic sockets

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"))
```

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

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

```
#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], )
```

force on SEA bushing from motor : $0.61921 N$

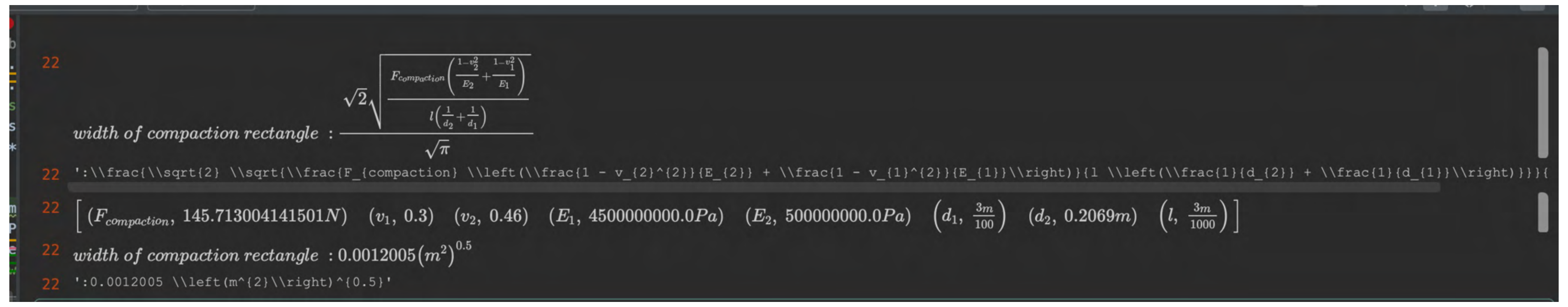
specific bearing load : $\frac{W_r}{bd}$

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

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

$\frac{1.88196071772231 N}{mms}$

Calculating the Hertzian contact Rectangle width between two cylinders



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

```
':\\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)}}}{
```

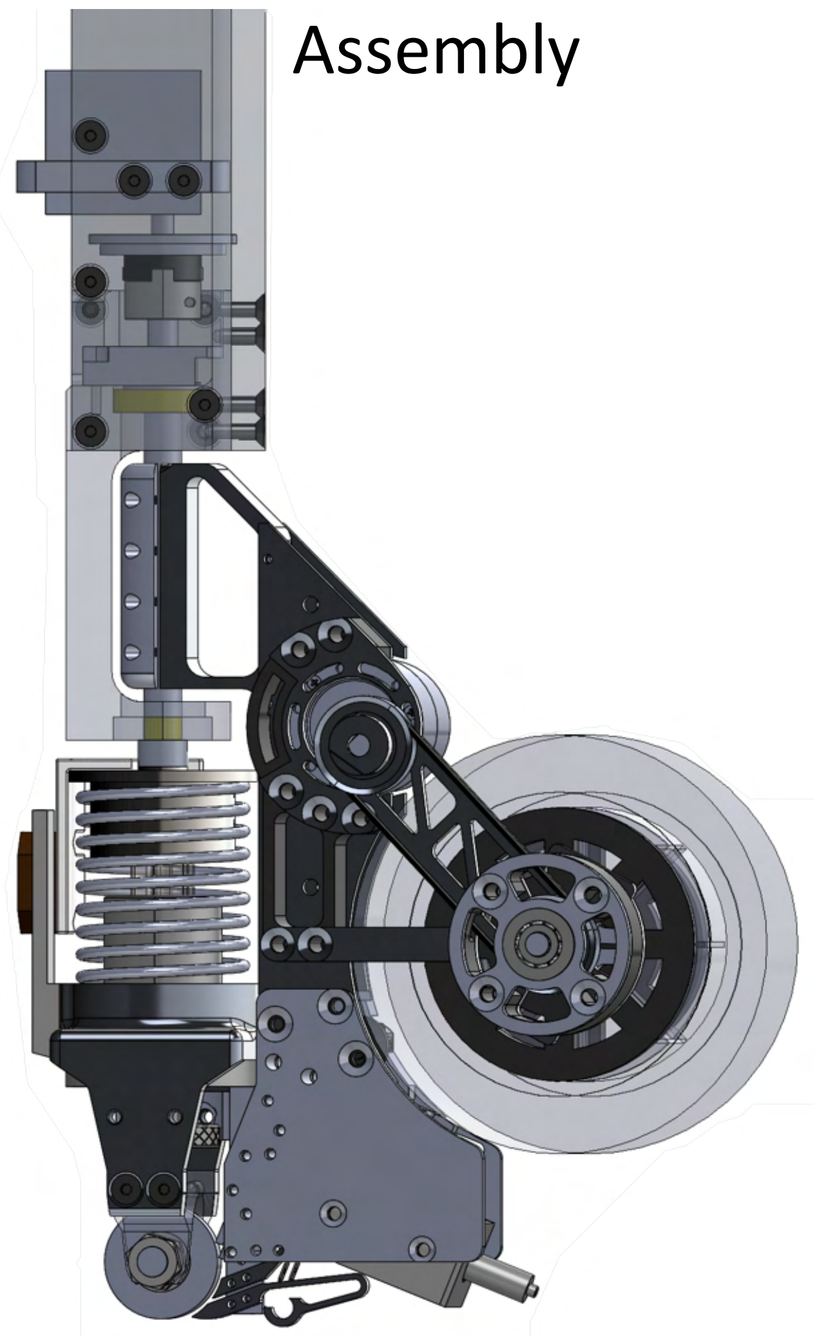
$\left[(F_{compaction}, 145.713004141501 N) \quad (v_1, 0.3) \quad (v_2, 0.46) \quad (E_1, 4500000000.0 Pa) \quad (E_2, 500000000.0 Pa) \quad \left(d_1, \frac{3m}{100}\right) \quad (d_2, 0.2069 m) \quad \left(l, \frac{3m}{1000}\right)\right]$

width of compaction rectangle : $0.0012005 (m^2)^{0.5}$

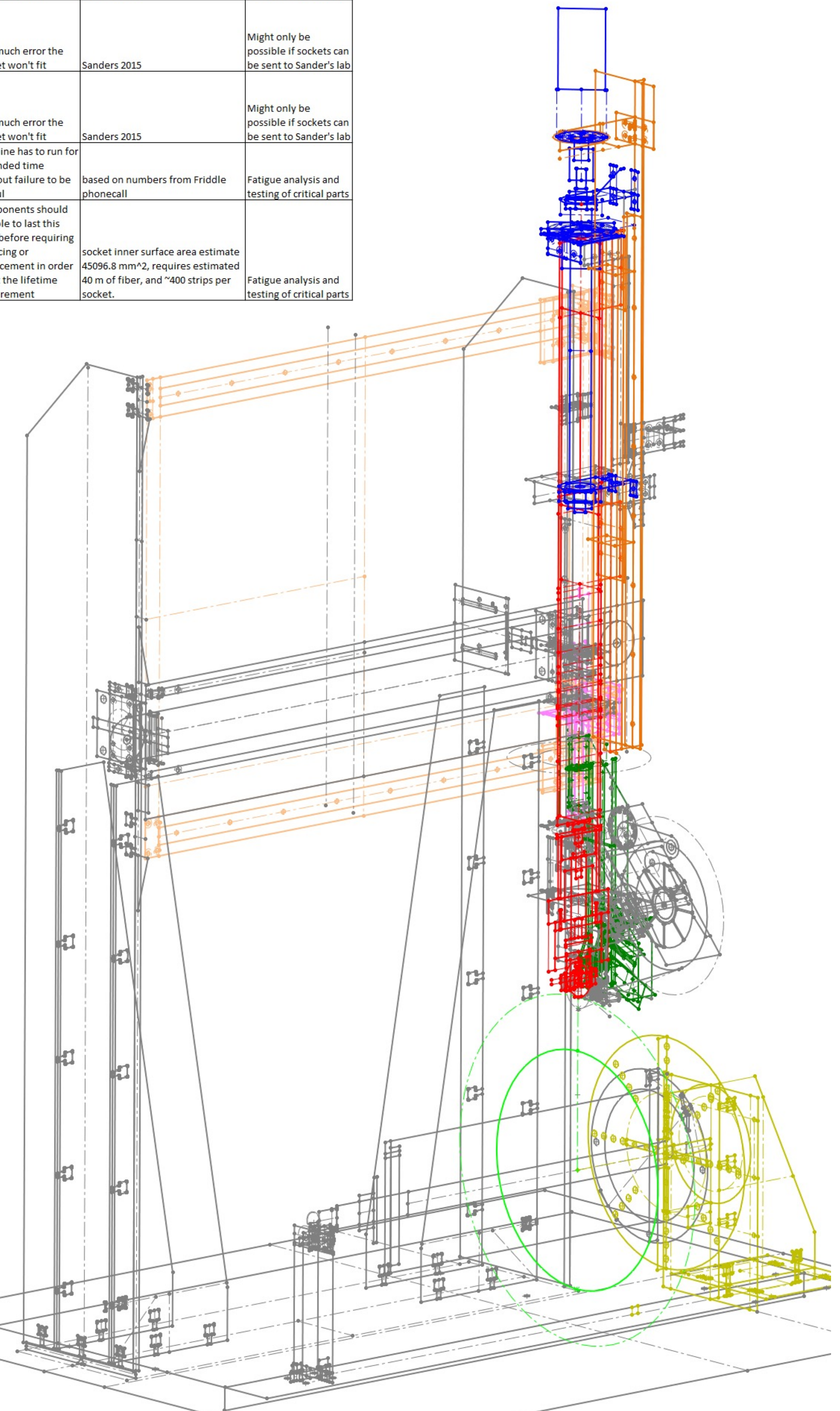
```
':0.0012005 \\left(m^{2}\\right)^{0.5}'
```

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

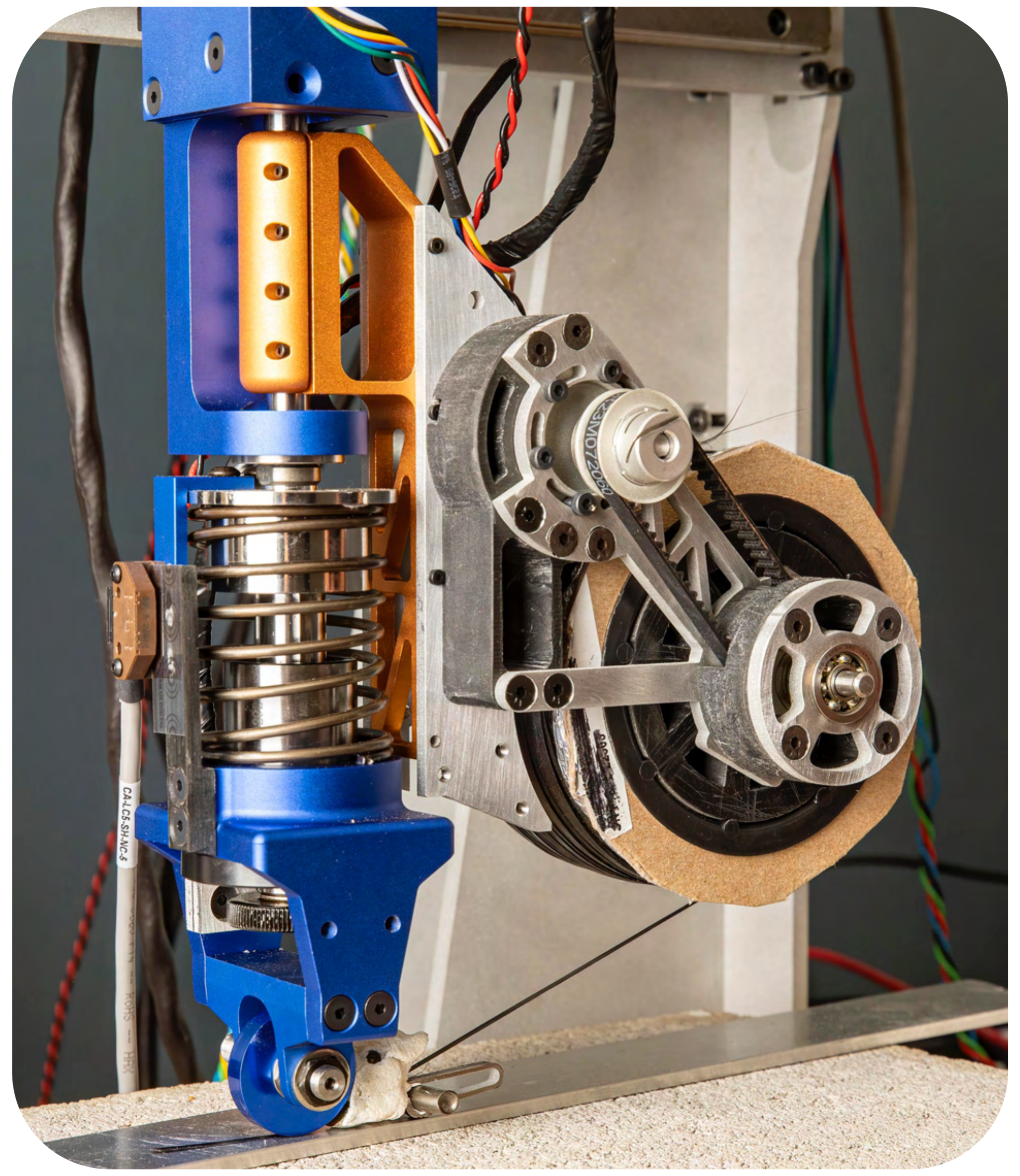


End Effector Assembled:

Series Elastic Compaction Actuator

Fiber Management

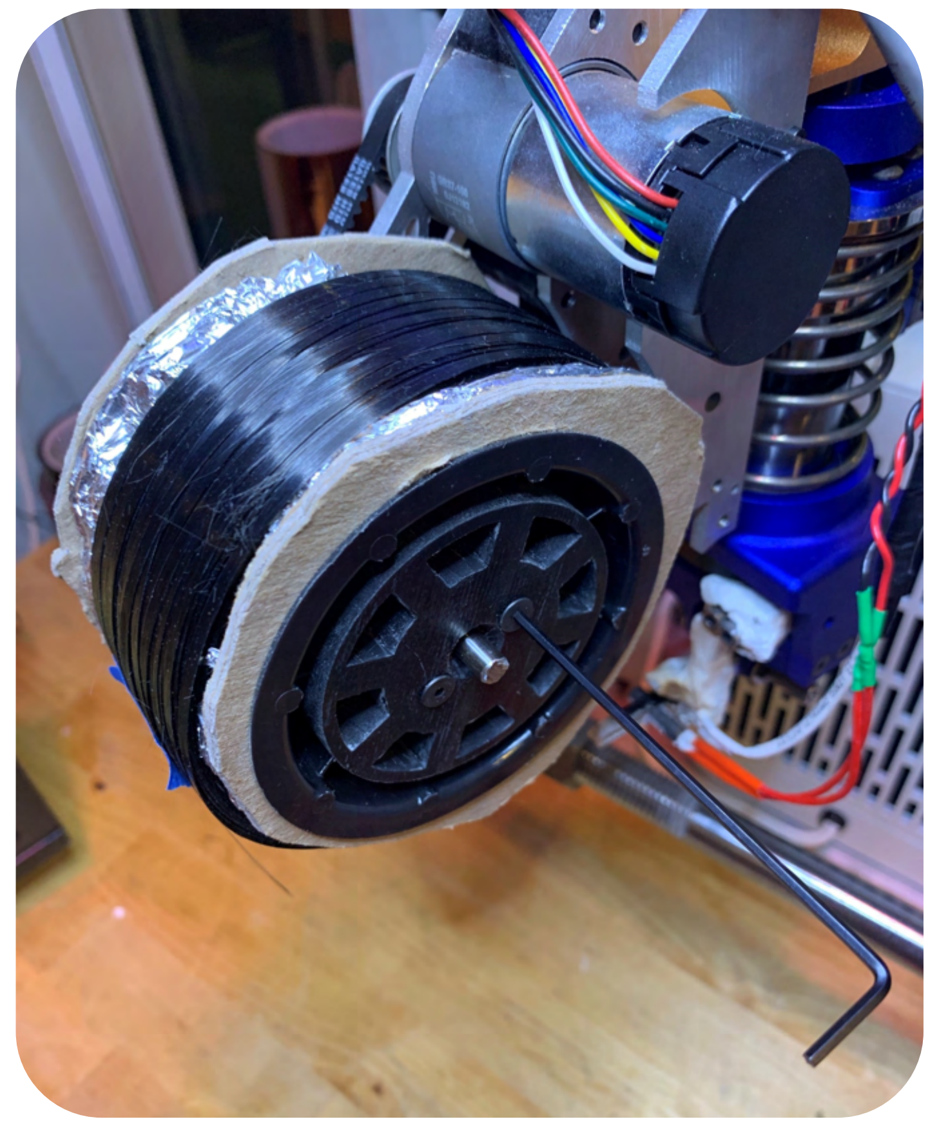
Fiber Orientation DOF



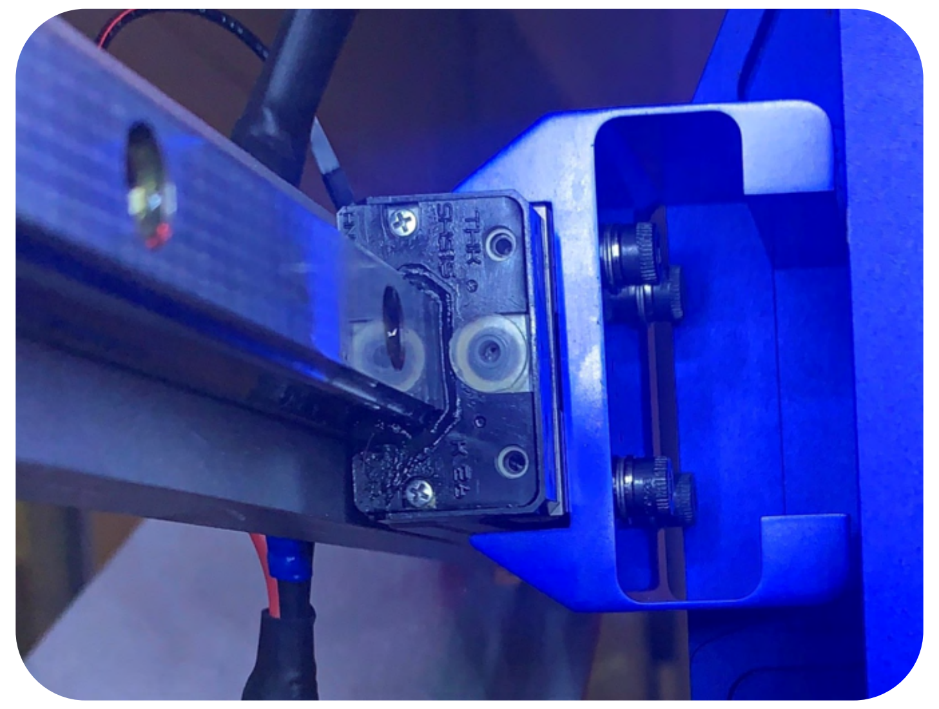
Series Elastic Actuator Components

A Few Closeups

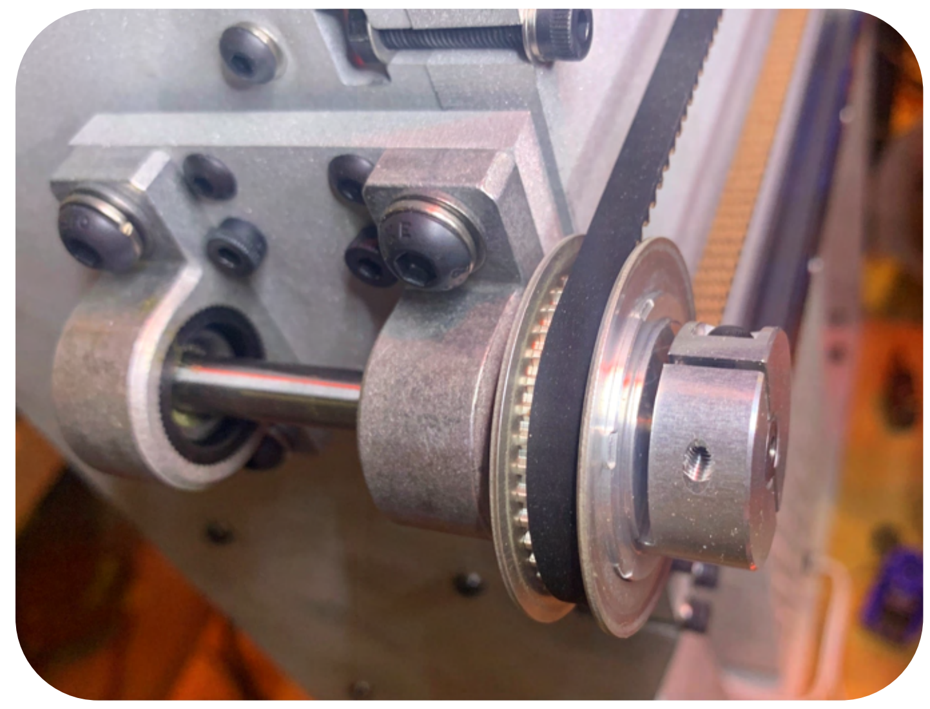
Remove 2 Screws to Replace Fiber Spool



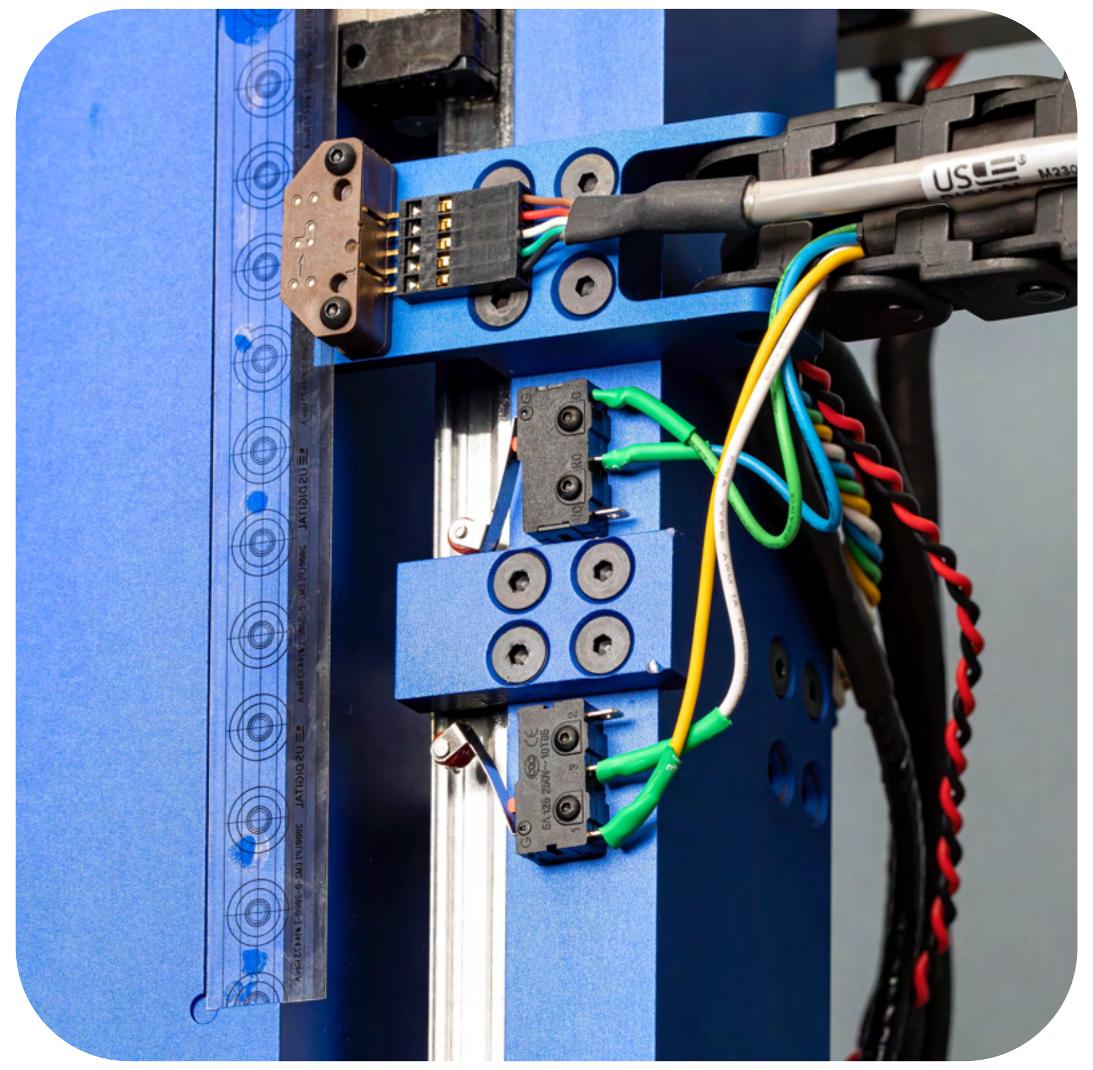
Bearing Flexure to Avoid Over-Constraint



Belt Tensioning

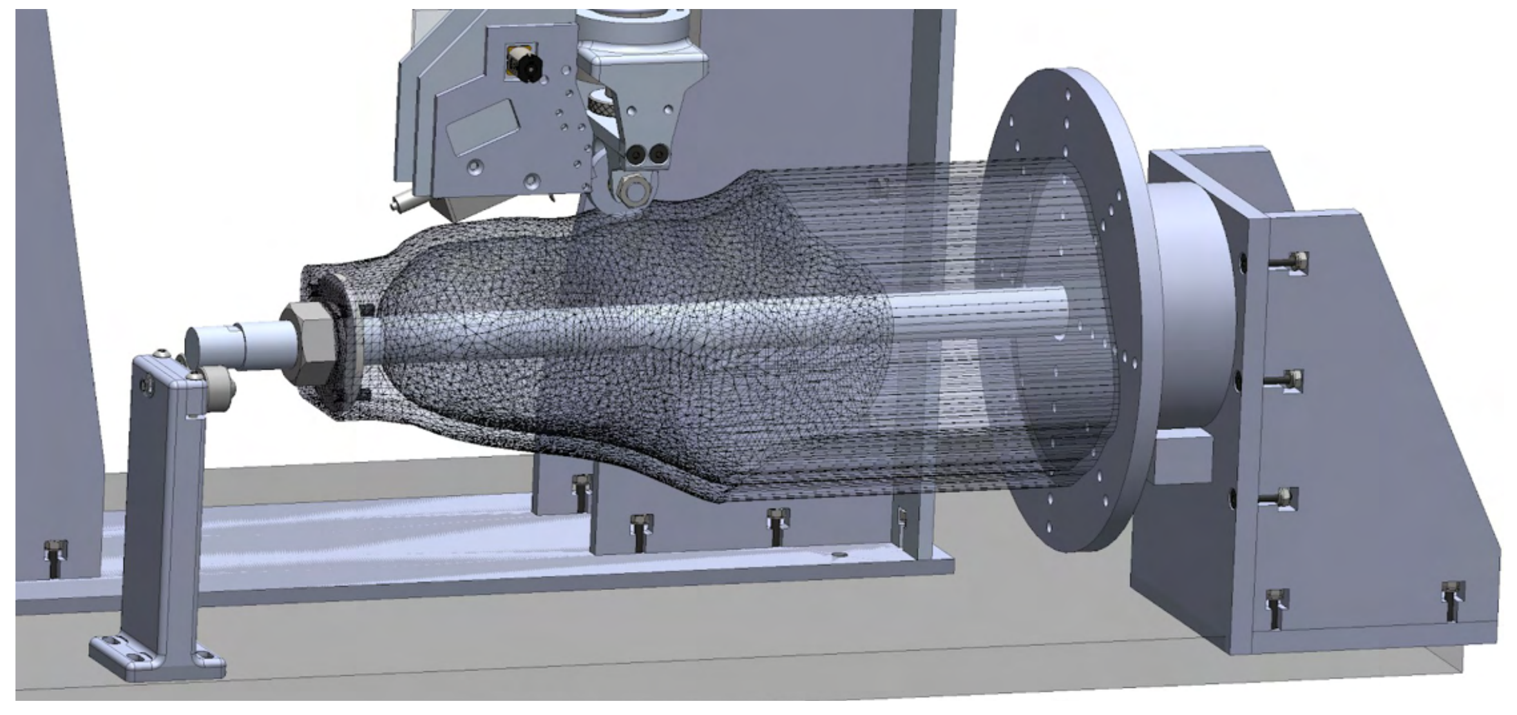


Encoder, Limit Switches, Hardstop



Workholding Support

Work Holding



Master’s Thesis: Software

Software Goals

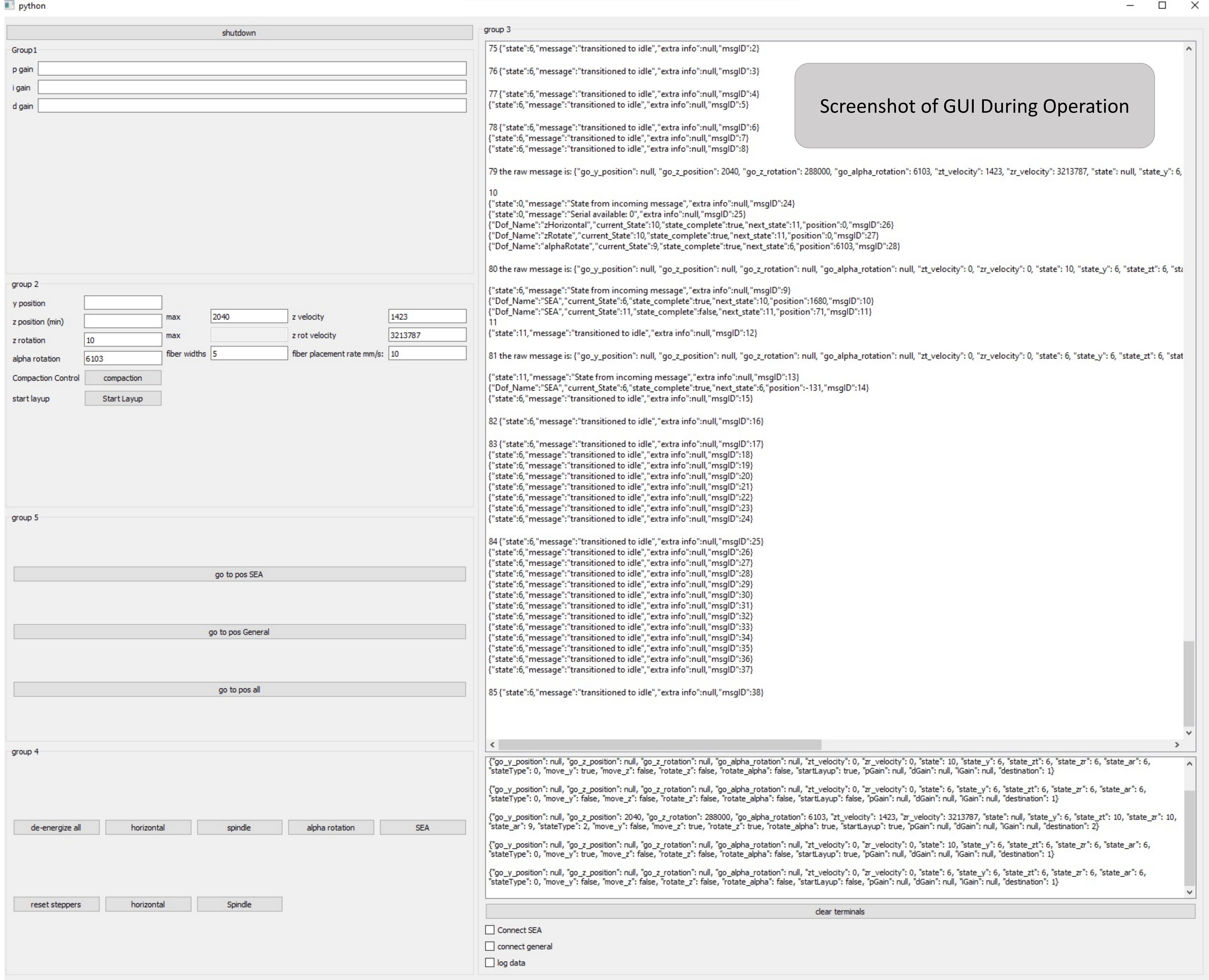
User interacts with GUI to send actions and parameters to machine
Machine parses input
Machine acts
Updates user while acting
Finish action and wait for next command
User can cancel action if necessary

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


Screenshot of GUI During Operation

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}
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78 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":6}
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10
{"state":0,"message":"State from incoming message","extra info":null,"msgID":24}
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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

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

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84 {"state":6,"message":"transitioned to idle","extra info":null,"msgID":25}
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"stateType": 0, "move_y": false, "move_z": false, "rotate_z": false, "rotate_alpha": false, "startLayup": false, "pGain": null, "dGain": null, "iGain": null, "destination": 1}

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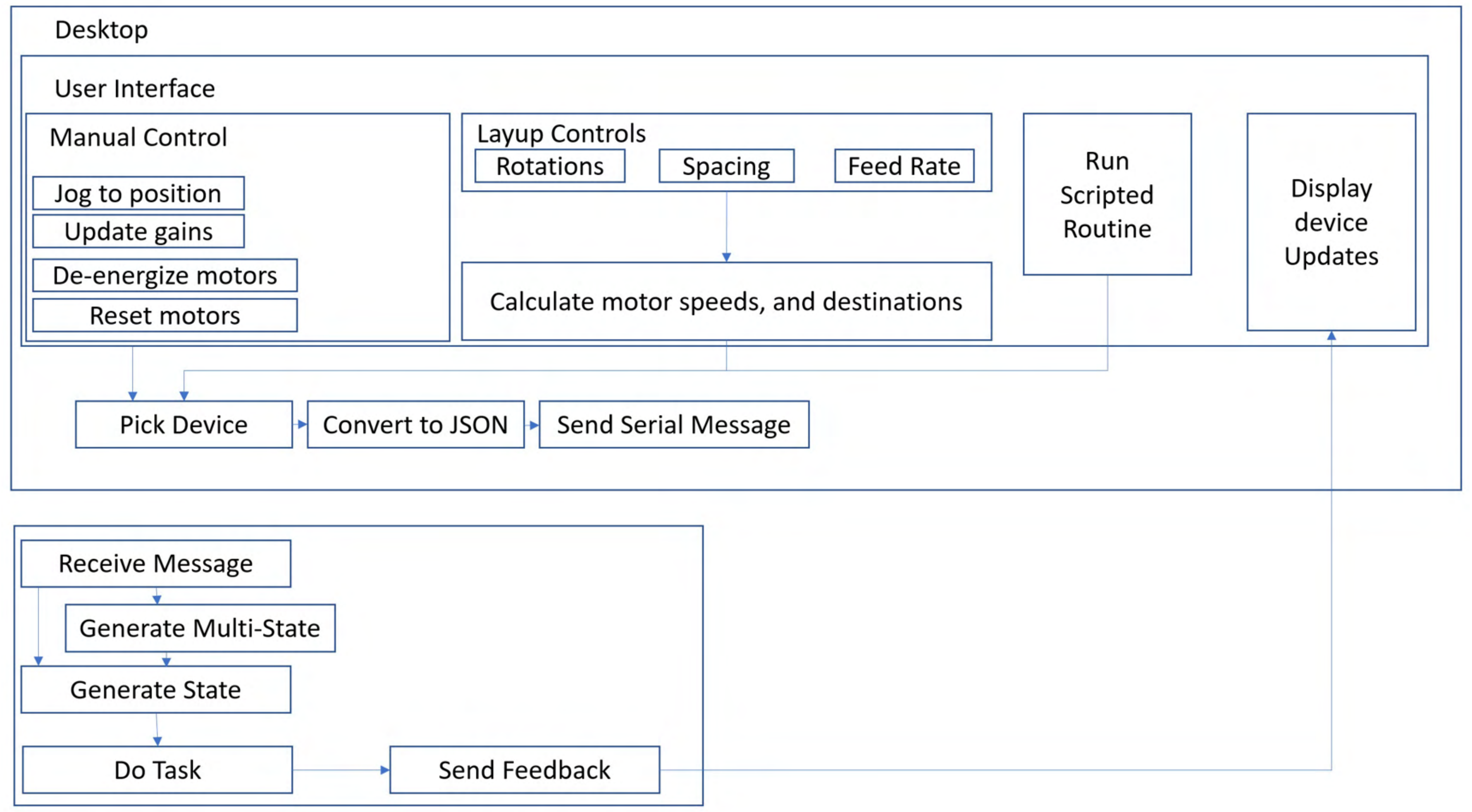
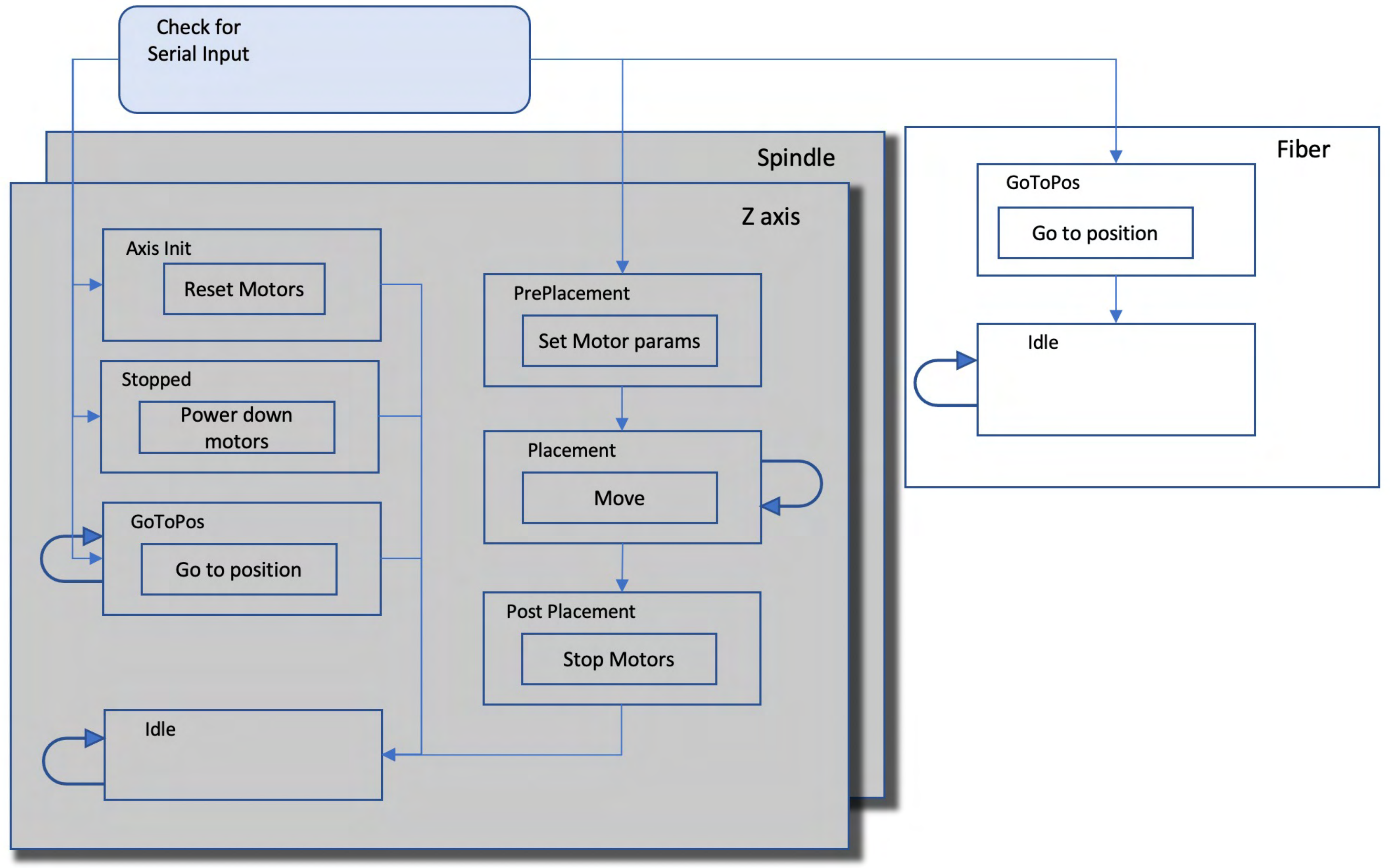
☐ Connect SEA
☐ connect general
☐ log data

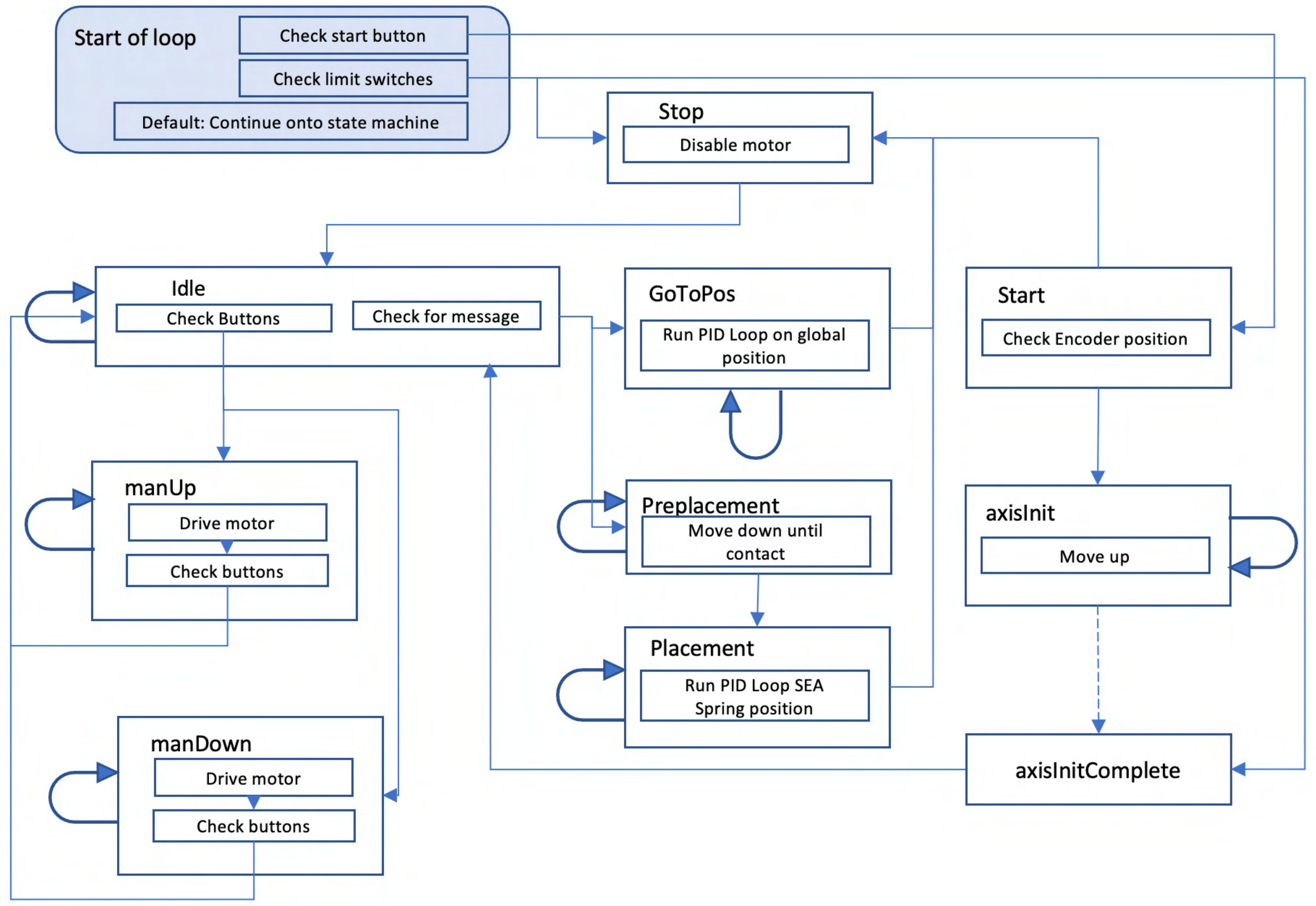
Desktop Program
Software Overview



SEA Compaction
State Machine



All Other DOFs
State Machine



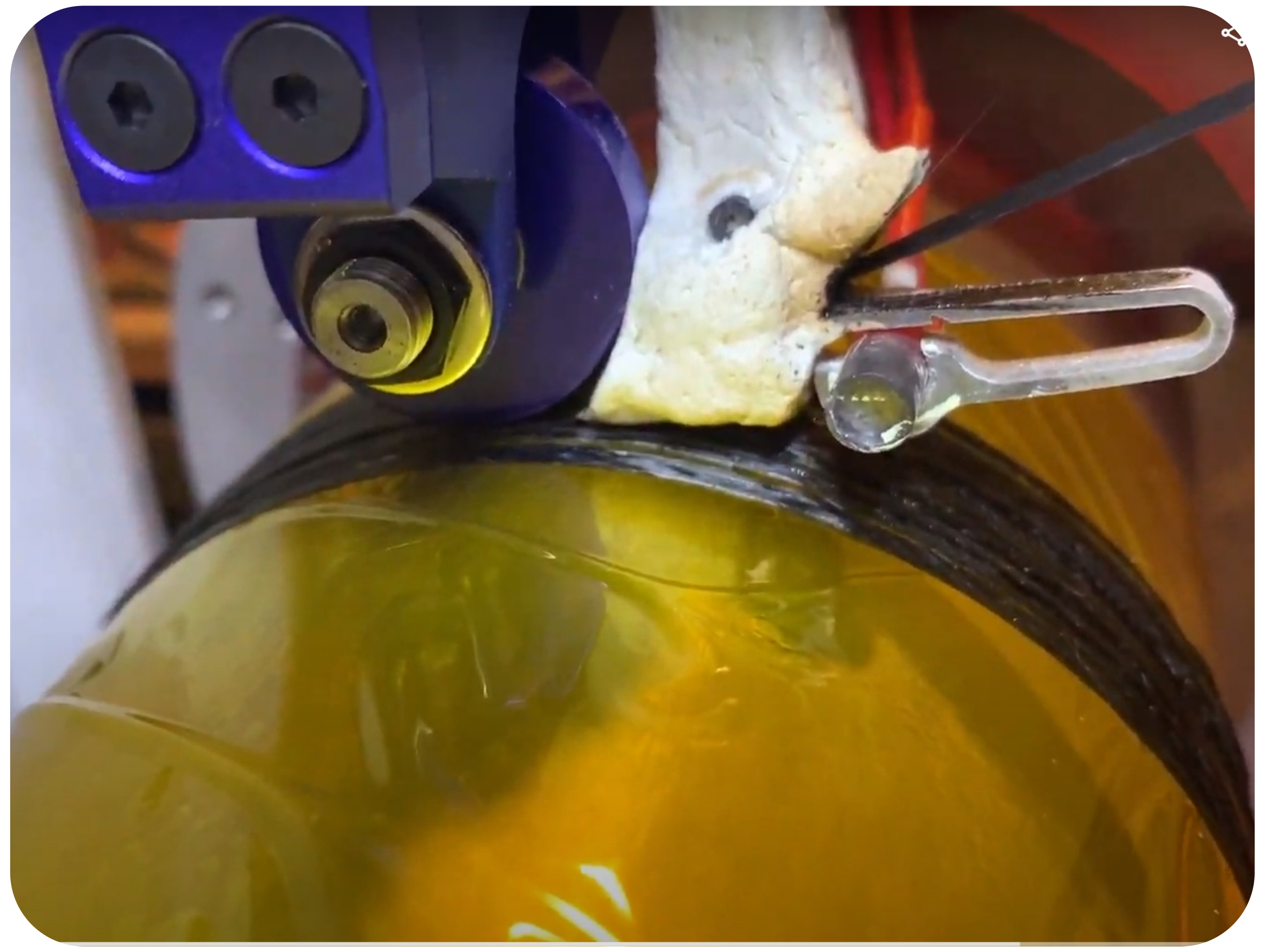
Master’s Thesis:
Testing and Evaluation

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.

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.

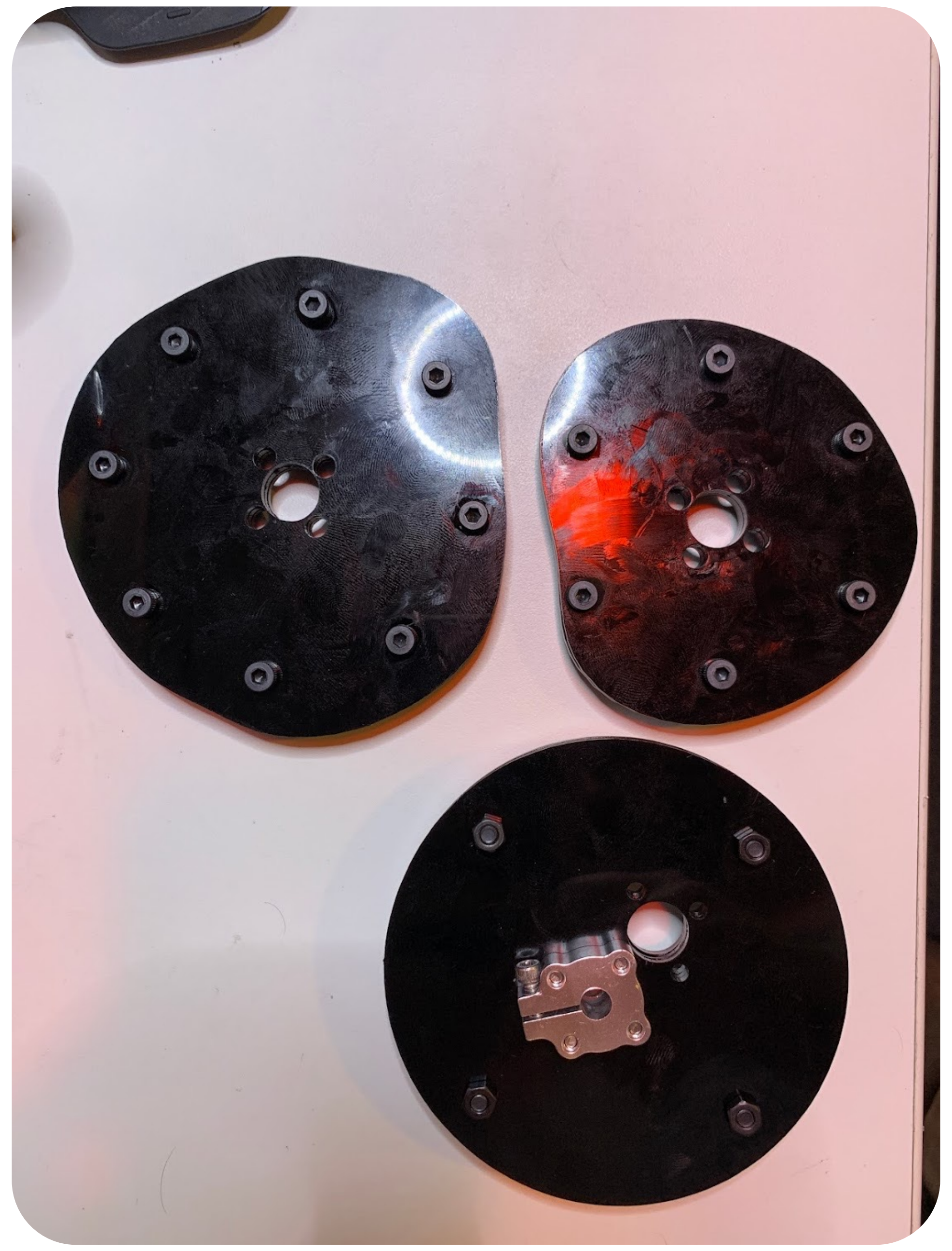


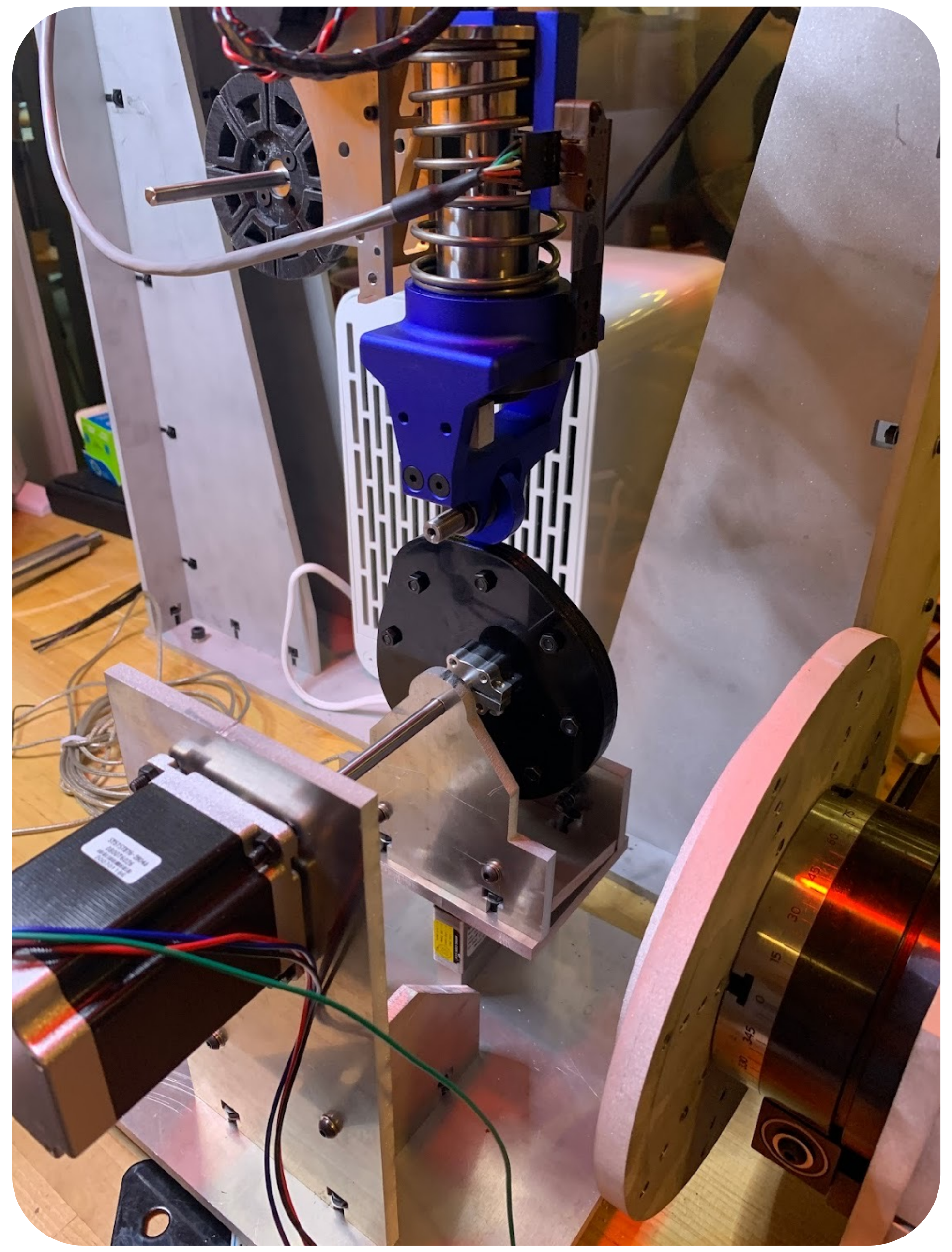
During development, the AFP machine produced lamination samples on a flat surface and a cylinder as shown in Figure 8-10. The cinder blocks were used as a sturdy raised surface as the Y axis cannot contact the table. The wrapping tests were done with an aluminum cylinder with an 114 mm diameter.3 This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

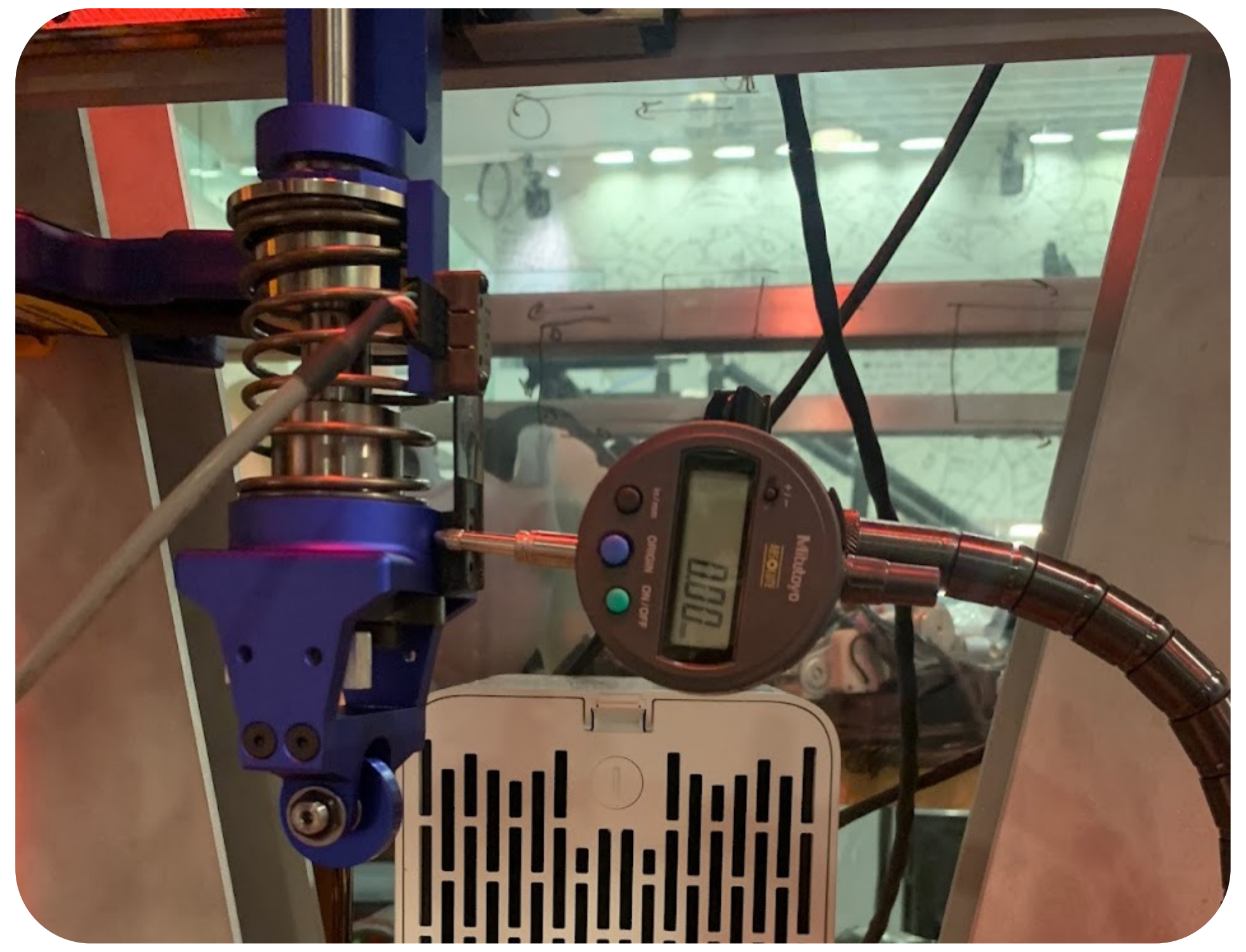
The flat strip tests were conducted when the Y axis, Z translational axis, and Fiber DOF could first be position controlled. The Z axis speed could not yet be adjusted, therefore the fiber feed-rate could not be adjusted. The strip produced is shown in Figure 8-10. This experiment demonstrated that the 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.

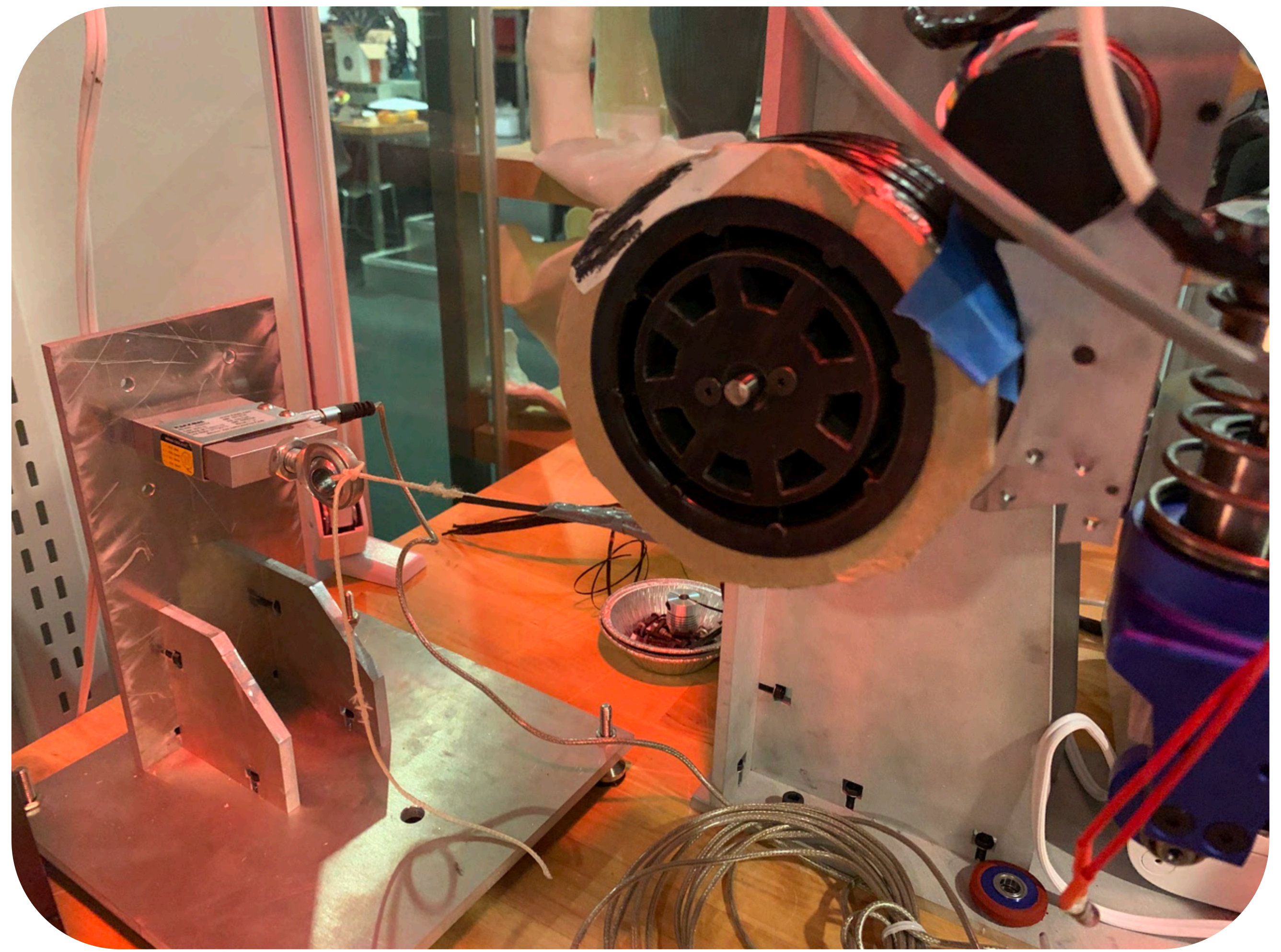


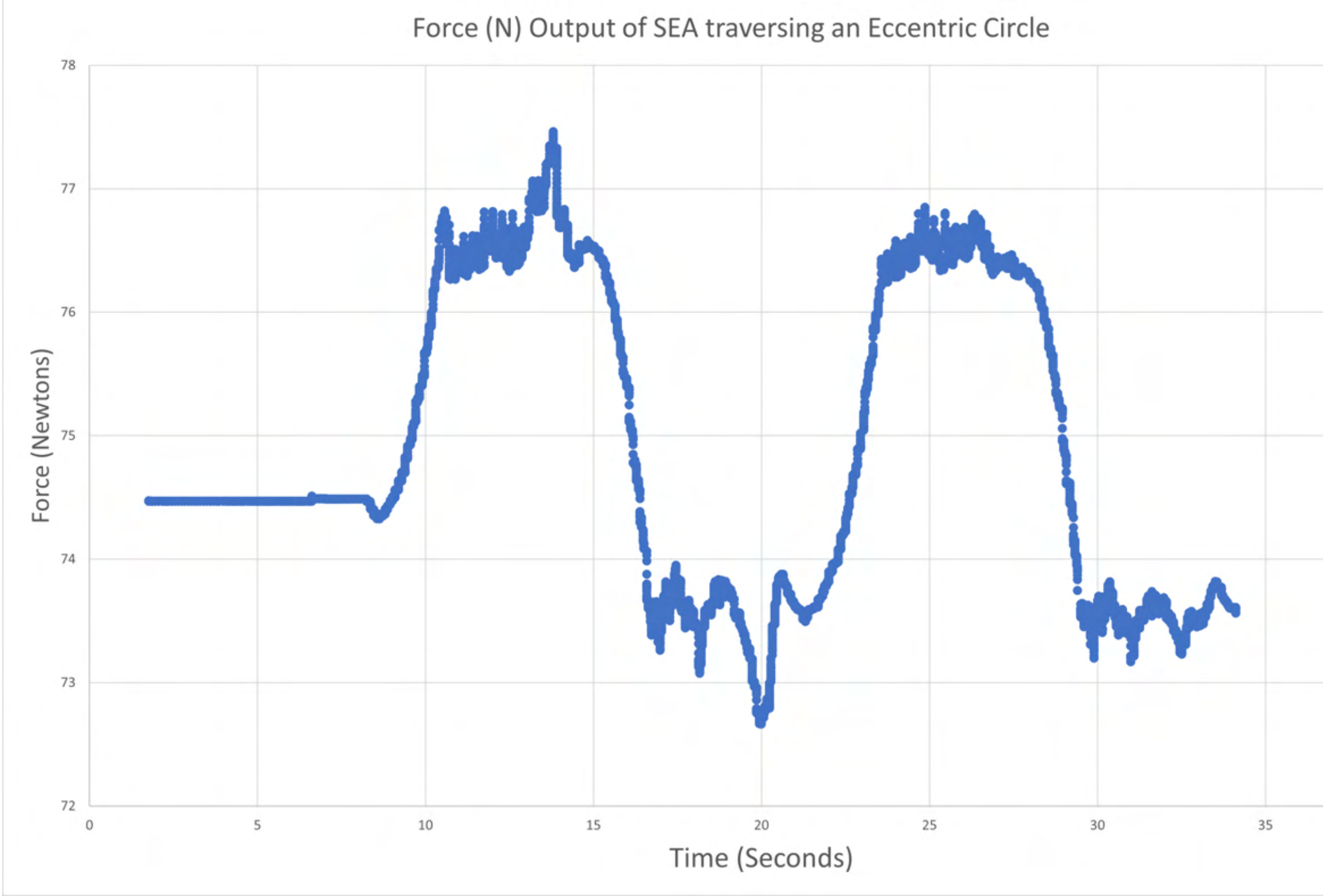


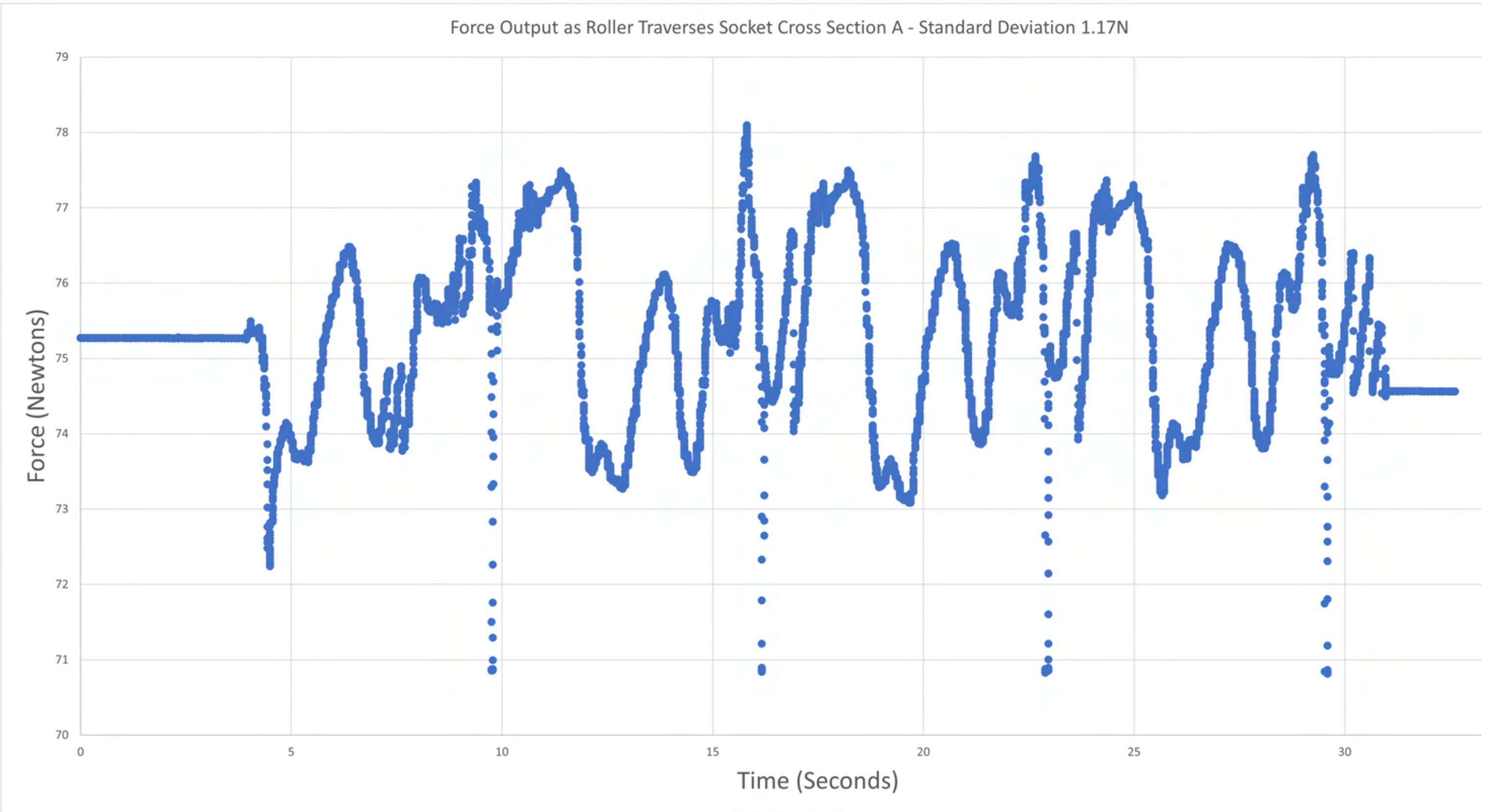


Fiber DOF Runout

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.