

MELD Project 30457 Task 3 and Task 4 - FASER Lab Final Report

Yiyan (Nick) Ruan, Melanie Anderson, Liam Chapin, Chaitanya (Chai) Sonalkar, Krishigan Yuvaraj, Erik Komendera
Virginia Polytechnic Institute and State University

I. Introduction

In accordance with Task 3.1 and Task 4.1 of MELD Project 30457 (*Robotic Metal Additive Mobile Solution for Repair and Upgrade of Components using MELD®*), the Field and Space Experimental Robotics (FASER) Lab has designed, developed, and analyzed a test rig to accommodate full-scale rail repair demonstrations. This test rig system consists of two primary components:

- 1) a one-DOF rail-feeding system capable of reliably passing a rail at a controlled rate into the operational envelope of the Hexapod, and
- 2) a support structure capable of bolstering the SCT Hexapod during operational conditions.

Because of the extreme loads involved in the MELD repair process, a rigorous analysis of these two subsystems was necessary to enable hardware purchasing and testing. To accomplish this, an iterative design approach was adopted in which Finite Element simulations were performed to inform subsequent design iterations until the integrity and performance of each subsystem (and the overall system) had been validated to a high degree of certainty. A discussion of this process and the corresponding results follows in Sections II - III.

In addition to ascertaining the structural capabilities of the system, the workspace of the system was also determined empirically via numerous simulations. Upon determining the barriers of the print head's performance, a set of optimal geometric relationships between the two subsystems could be defined and desired performance criteria could be verified. Related discussions can be found in Section IV.



Fig. 1 The Hexapod and Rail Mover system

II. Rail Mover System

A. Introduction

The rail mover system employs a lead screw, rail, and carriage system to advance a rail in one degree of freedom, while the MELD print head deposits material onto the rail's top surface. This brief report outlines the basic structure of the rail mover system design and offers a comprehensive description of the Finite Element Analysis conducted to evaluate its structural integrity.

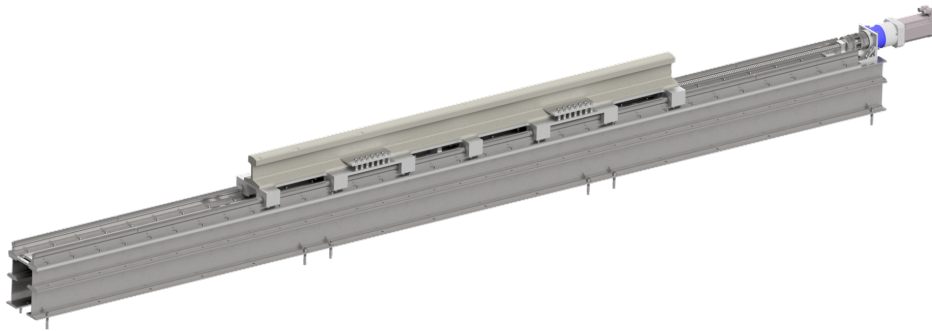


Fig. 2 General Rail Mover Concept

B. Structure

The system comprises two major components: the rail and carriage feed system and the underlying support structure. The top moving piece is actuated by a 25mm ball lead screw, which is powered by a BECKHOFF servo motor. This 8ft long lead screw, along with the ball screw nut on the end of the moving platform, provides the system with an extended stroke as defined by MELD's operational requirements. In its current configuration, the entire system is anchored to the ground using 16 concrete anchors positioned around the edges of the underlying support structure. However, as discussed in Section IV, it is likely that the entire rail system will be elevated. Once the optimal location of the rail is determined, steel I-Beams will be positioned below the rail system support structure to raise it. In this scenario, the feed system's base plate will be mechanically fastened to the I-Beams, which will be anchored to a leveled section of the concrete floor. It is important to note that the following analyses were conducted prior to the insertion of I-Beams into the assembly; however, subsequent analyses indicate that raising the rail in this manner does not significantly affect the results.

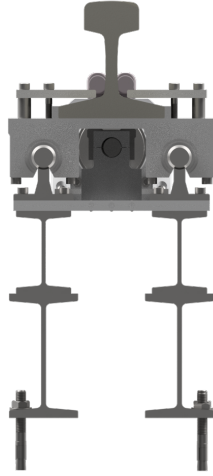


Fig. 3 Depiction of the dynamic component (upper) and support structure (lower)

To reliably actuate the 8ft long rail under a vertical load of 12000 lbs and a side load of 3000N, the support rail system was introduced. A total length of 4800mm support rail with 30mm diameter shafts was chosen to enable the complete traversal of the 8-ft long rail. With 14 ball-bearing carriages evenly placed underneath the railway track support plate, the motor can translate the rail with relatively low frictional losses ($f_s \approx 0.04$). The lead screw (and the rail) is actuated by a BECKHOFF servo motor and gearbox combination capable of producing a maximum torque of 250 N-m. To enhance safety, the gearbox output shaft is connected to the lead screw via a flexible coupling system, as depicted in Figure 4, which allows for small deflection between the two ends and enables continuous rotation of the lead screw even under deformation.

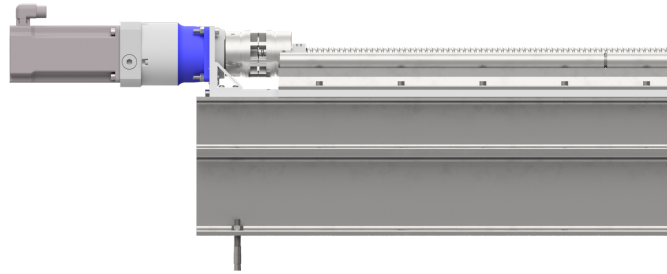


Fig. 4 BECKHOFF servo motor system with flexible shaft coupling

To reduce costs and enhance manufacturability, the base support plates were divided into four parts, which can be easily assembled via bolts at the operation site. To secure the rail, four screw clamps were installed on the moving structure (two on each side). The clamp is anchored by screws on the outer side of the rail support plate, constrained by standoffs. The screws on the inner side can be extended to lock the rail in place with a strong clamping force, as illustrated in Figure 5.

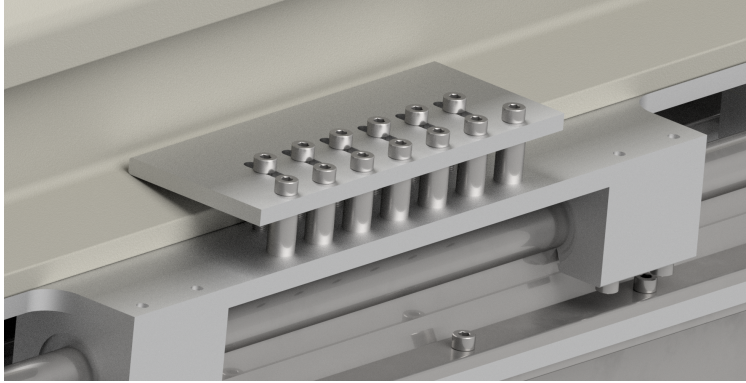


Fig. 5 Clamping mechanism on the train track rail

C. Finite Element Analysis

The FEA of the Rail Mover system was conducted with the following constraints as shown in Figure 6:

- The bottom surface of the I-beams were considered fixed to the ground (Tag G and H).
- A 250 N-m torque (tag D) was applied to the motor output shaft as the motor assembly actuates the rail.
- A 5000 N clamping load (Tag E) was applied on the clamp surfaces to clamp the railway track in place.
- A reaction force (Tag F) was applied to the bottom of the support plate.
- A 12000 lb vertical force (Tag A) was added to the top of the rail in a series of positions
- A 3000 lb side load (Tag C) caused by the spinning print head was introduced to the contact surface through a remote point.
- A gravity field (Tag B) was applied to the system to simulate the weight load.

The whole model was meshed into a combination of tetrahedral and octahedral elements with a width of 20mm as shown in Figure 7.

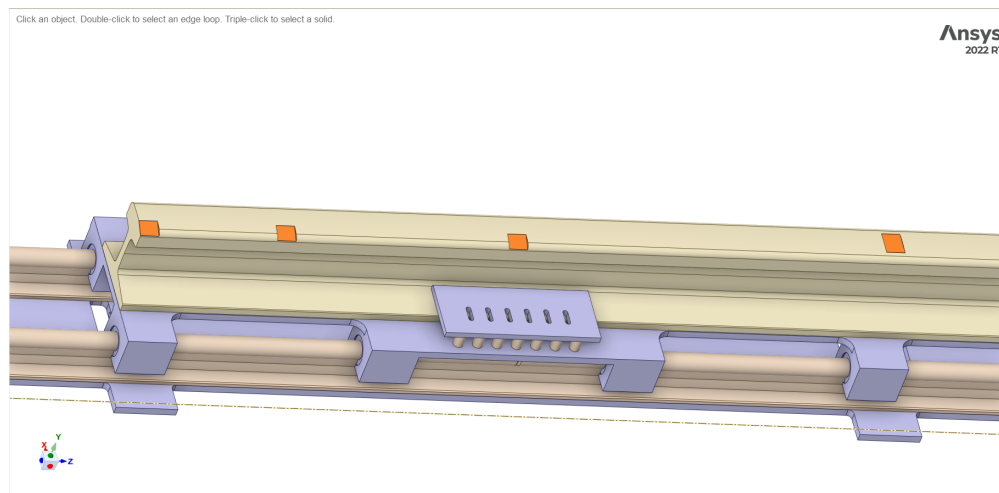


Fig. 6 Four print head loads are placed in locations highlighted in orange

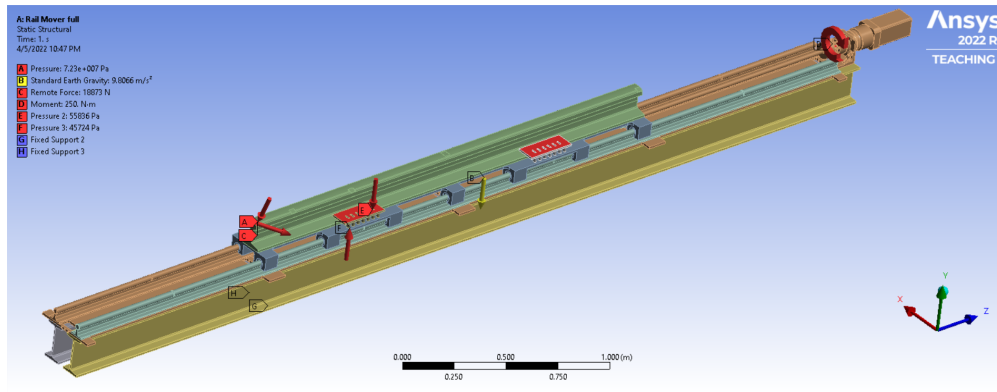


Fig. 7 Boundary conditions and loads applied on the system

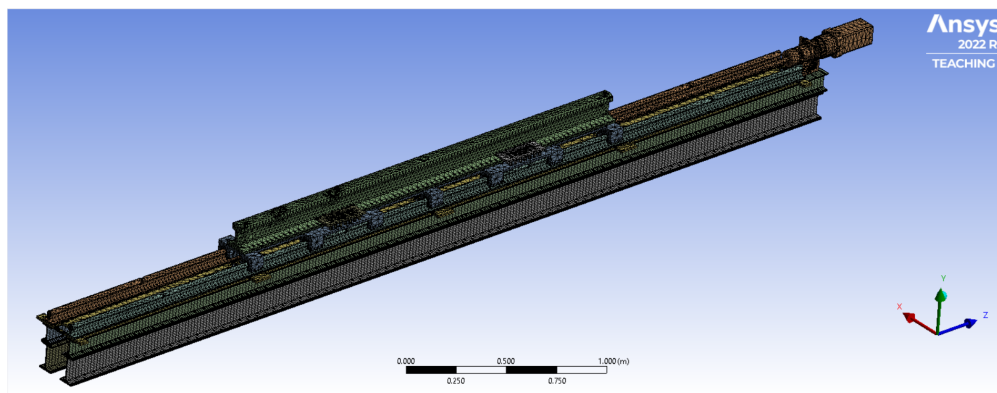


Fig. 8 Mesh with element size: 20mm

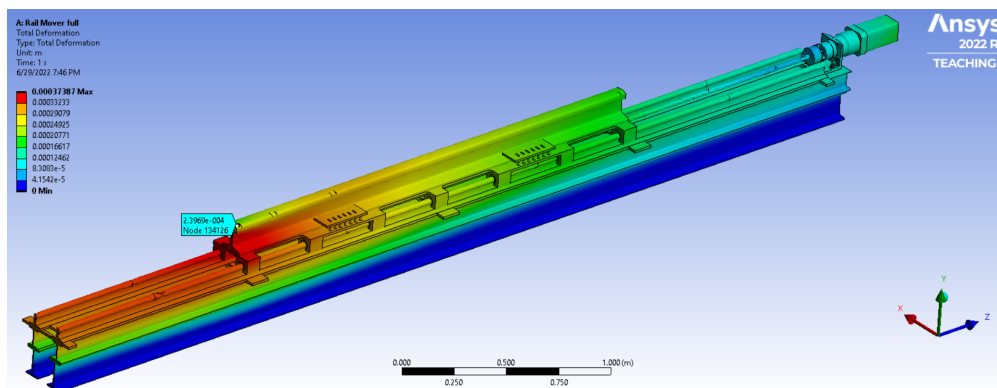


Fig. 9 Maximum displacement at the print head: 0.23969mm

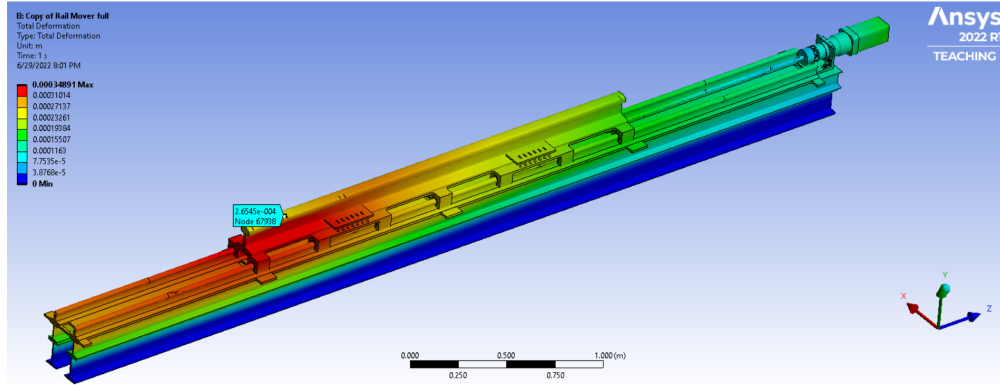


Fig. 10 Maximum displacement at the print head: 0.26545mm

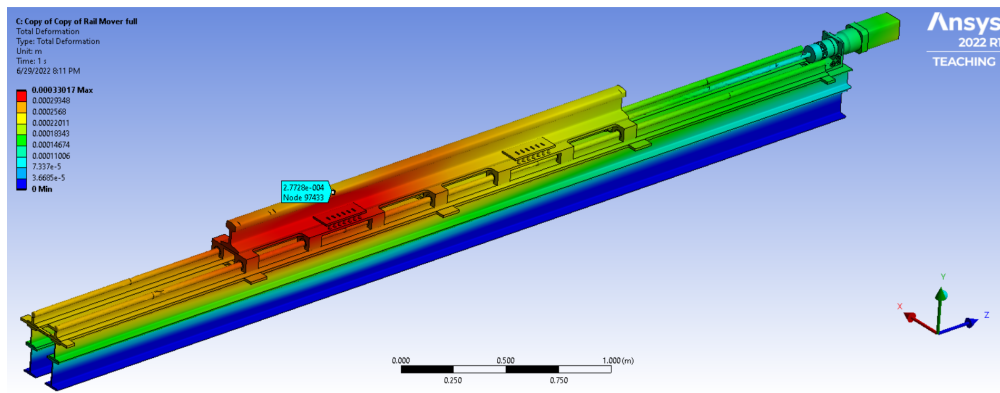


Fig. 11 Maximum displacement at the print head: 0.2772mm

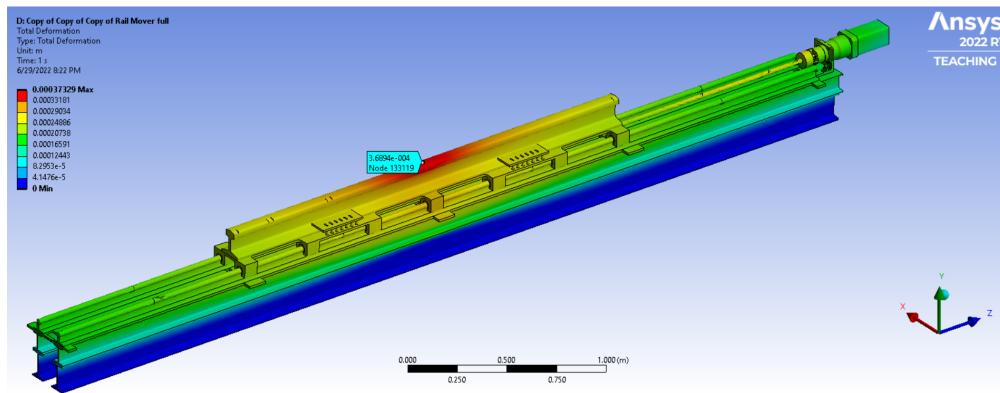


Fig. 12 Maximum displacement at the print head: 0.36894mm

With the print load applied at various locations (illustrated in Figures 9 - 12), the maximum deflection ranged from 0.128 mm to 0.389 mm. It was observed that the greatest deformation occurs at the end of the rail when the load is applied at a 20-degree angle around the axis of the rail. Conversely, the smallest deflection is observed when the load is applied to the center of the rail.

D. Modification

After the initial assembly of the rail mover, the team encountered numerous challenges that hindered its full functionality. The primary issue arose from the susceptibility to low-frequency vibrations caused by the sheer length of the lead screw. When the rail carriage extends to a certain point, the diameter of the lead screw becomes inadequate to withstand the rotational force exerted by the printing bar. The continuous compression and tension forces on the lead screw result in buckling and vibration, posing a risk of damaging print heads and loosening screws and bolts on the rail mover, exacerbating the problem over time.

To address these issues, a series of modifications have been implemented to fortify the rail mover system. Firstly, six pairs of cross braces— one pair on each end of the three I-Beam sections— have been added between the base rail support structures to enhance structural rigidity. In the previous design, the I-beam support structures were solely connected by a thin aluminum plate at the top, which was identified as being susceptible to the low-frequency vibration induced by the spindle contact forces. With the addition of the x-bracing bars, the vibration magnitude has been greatly reduced to a point where it is not visually perceptible.



Fig. 13 Rail Base Cross Bracing

Secondly, the aluminum train track rail clamps have been replaced with stainless steel ones to eliminate slippage between the rails and carriages, a concern observed in previous test prints. With a much harder material, the stainless steel rail clamps can transfer more clamping force directly onto the edge of the train track rail. No further slippage was noticed after the modification.



Fig. 14 Stainless rail clamp

Additionally, a new lead screw mount fastening system has been added to securely hold the bearing mounts in place. The previous design only supported the lead screw mounts at the bottom. However, after the test print, the team noticed that in addition to the downward force, the spindle also introduced a lateral force into the lead screw system that loosened the lead screw mounts over time. The new lead screw mount fastening system secures the mounts in both vertical and lateral directions, eliminating any possibility for the mounts to come loose.

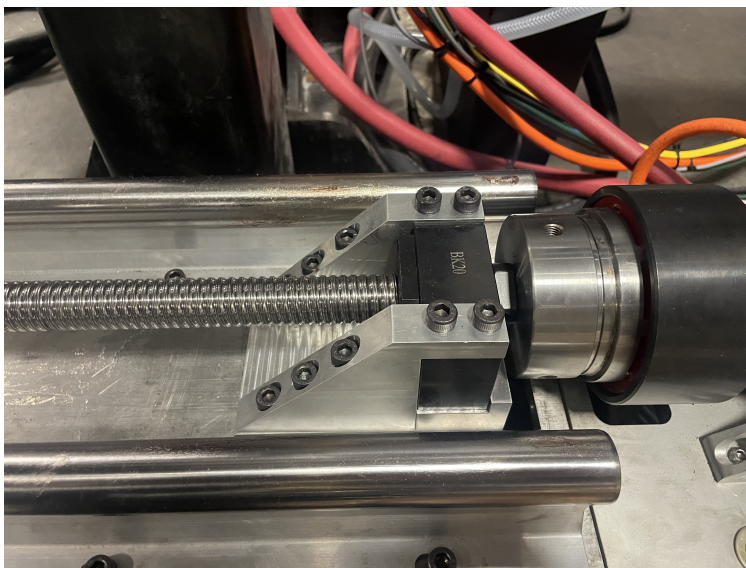


Fig. 15 Lead Screw Brace (Motor Side)



Fig. 16 Lead Screw Brace (Rail Side)

III. Hexapod Support Structure

A. Structure

The support structure was designed to mount the Hexapod laterally and withstand the dynamic reaction forces of the print head during operation. The supporting members of the stand consist of square tubes measuring 6 inches in width and 3/8 inch in thickness. A bracket is used to mount the Hexapod onto these supporting members. Bolted joints were chosen for assembly due to the size of the structure, facilitating manufacturing and assembly processes. The stand is further secured to the ground using foundation bolts.

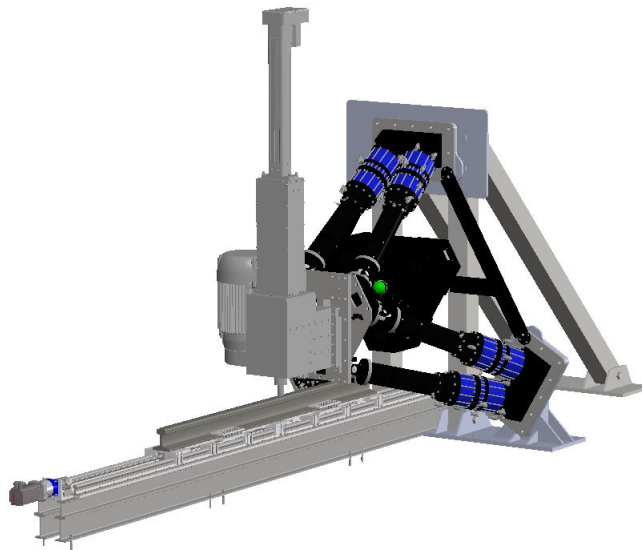


Fig. 17 Hexapod Stand Render

B. Finite Element Analysis

A finite element analysis (FEA) model of the stand was developed in ANSYS Workbench 2021 Software. The square tubes and the brackets were modeled using 8-node shell elements, as the thickness of the tube and bracket is small compared to their length. Additionally, a Hexapod was modeled using 1-D rigid elements to distribute the reaction forces on the mounting bracket. The model was utilized to simulate various dynamic load conditions through quasi-static analysis. The dynamic load conditions, simulation parameters, and results were decided according to possible hexapod motions and motion queuing required for printing across the rail surface. The loading scenarios considered for analyses are summarized as follows -

- 1) Translation about X-axis - This load case simulated the scenario where the print head moves laterally across the rail, along the x-axis.
- 2) Rotation about X-axis - This load case simulated the scenario where the print head rotates about the x-axis. The point of material deposition remains the same, however the angle of printing changes simulating a pitch motion.
- 3) Translation about Y-axis - This load case simulated the scenario where the print head moves longitudinally across the rail, along the y-axis.
- 4) Rotation about Y-axis - In this load case, the print head rotates about the Y-axis. This scenario simulations roll motion.



Fig. 18 Mesh with 8 mm*-node Quadrilateral elements

1. Translation about X-axis

Two different approaches were considered when simulating the behavior of the stand under varying loads. For the first case, the forces, i.e., the weight of the print head and the reaction from the contact were scoped to front of hexapod structure, where the print head is attached to the hexapod. In the second case, only the weight of the print head was scoped to the front of hexapod structure. The reaction forces were resolved along the arms of the hexapod and were scoped to the individual mounting plates on which they acted upon.

Case 1 - Boundary Conditions:

- The Hexapod base is fixed to the ground.
- Fixed joints are assigned to bolted connections.
- The ANSYS limitations require the application of force to a single location. Therefore, translation was modeled using five remote forces at equal intervals along the length of the motion. These forces are activated only at specific sub-steps, simulating the translation motion in a quasi-static manner.
- The weight of the print head was also simulated in a similar manner.

A: Static Structural
 Static Structural
 Time: 2 s
 Items: 10 of 22 indicated
 16-06-2022 00:23

- A** Remote Force: 55148 N
- B** Remote Force 2: 9000 N
- C** Remote Force 3: 55148 N
- D** Remote Force 4: 55148 N
- E** Remote Force 5: 55075 N
- F** Remote Force 6: 55071 N
- G** Remote Force 7: 8100 N
- H** Remote Force 8: 8100 N
- I** Remote Force 9: 8100 N
- J** Remote Force 10: 8100 N

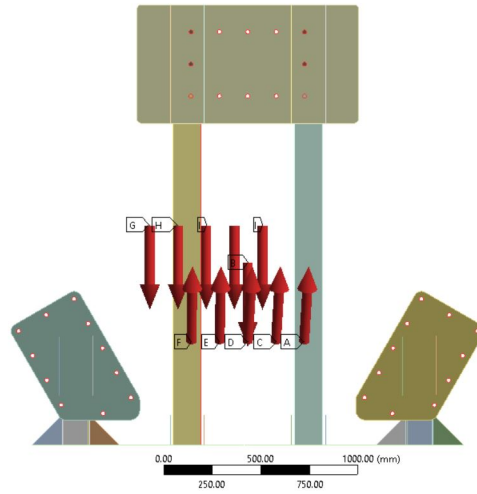


Fig. 19 Boundary Condition

Results:

A: Static Structural
 Equivalent Stress
 Type: Equivalent (von-Mises) Stress - Top/Bottom
 Unit: MPa
 Time: 5 s
 Deformation Scale Factor: 1.0 (True Scale)
 16-06-2022 00:41

585.16 Max
 520.14
 455.12
 390.1
 325.09
 260.07
 195.05
 130.03
 65.017
0.00018605 Min

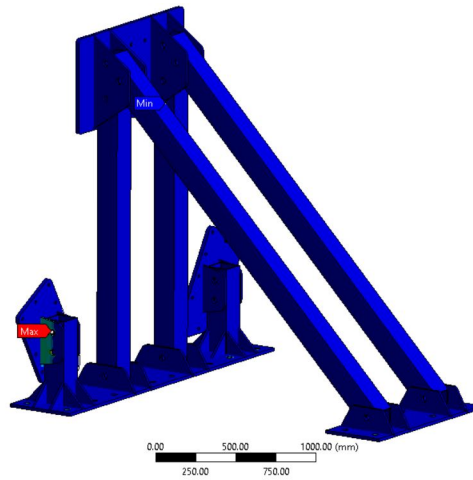


Fig. 20 Maximum Stress = 585.16 MPa

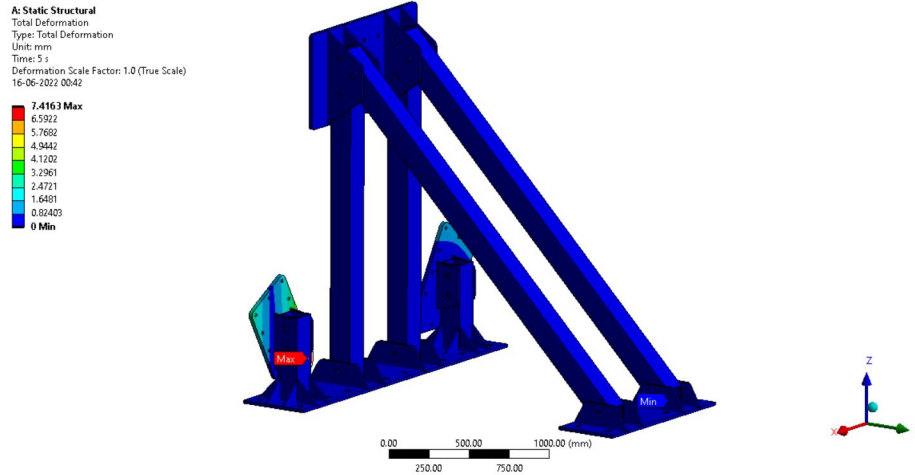


Fig. 21 Maximum displacement = 7.4163 mm

Case 2 - Boundary Conditions:

- The Hexapod base is fixed to the ground.
- Fixed joints are assigned to bolted connections.
- The weight of the print head is modeled as a point mass, and a remote force scoped to the mounting brackets is used to simulate the weight of the Hexapod.
- The force exerted by the print head through each arm of the Hexapod is calculated using a low-fidelity MATLAB model and scoped to the mounting plate using a remote force.

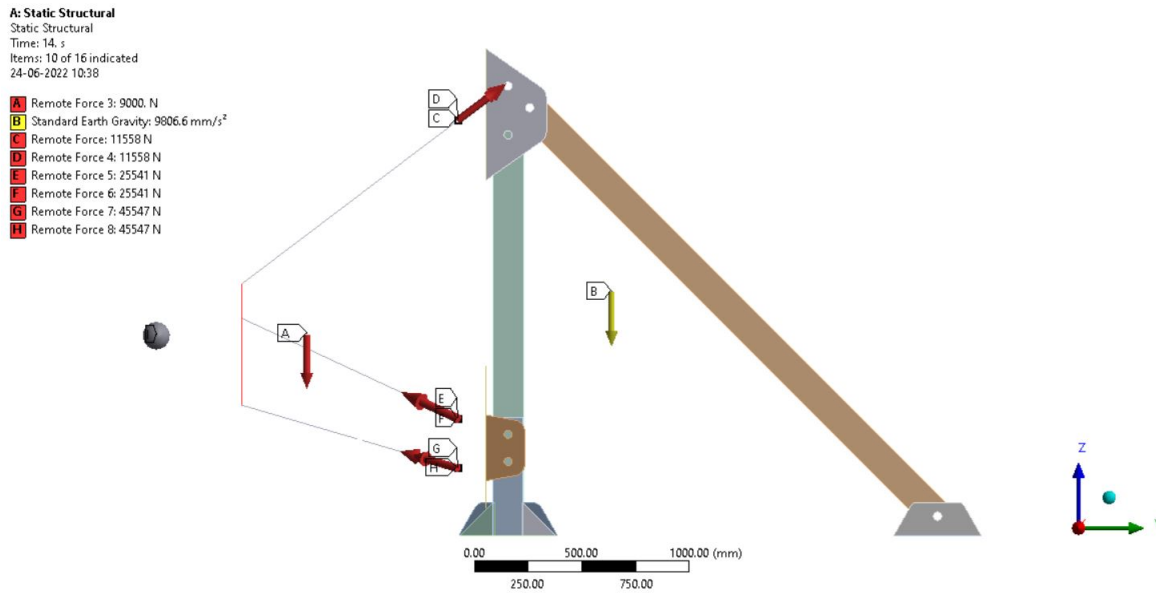


Fig. 22 Boundary Condition at Step 1

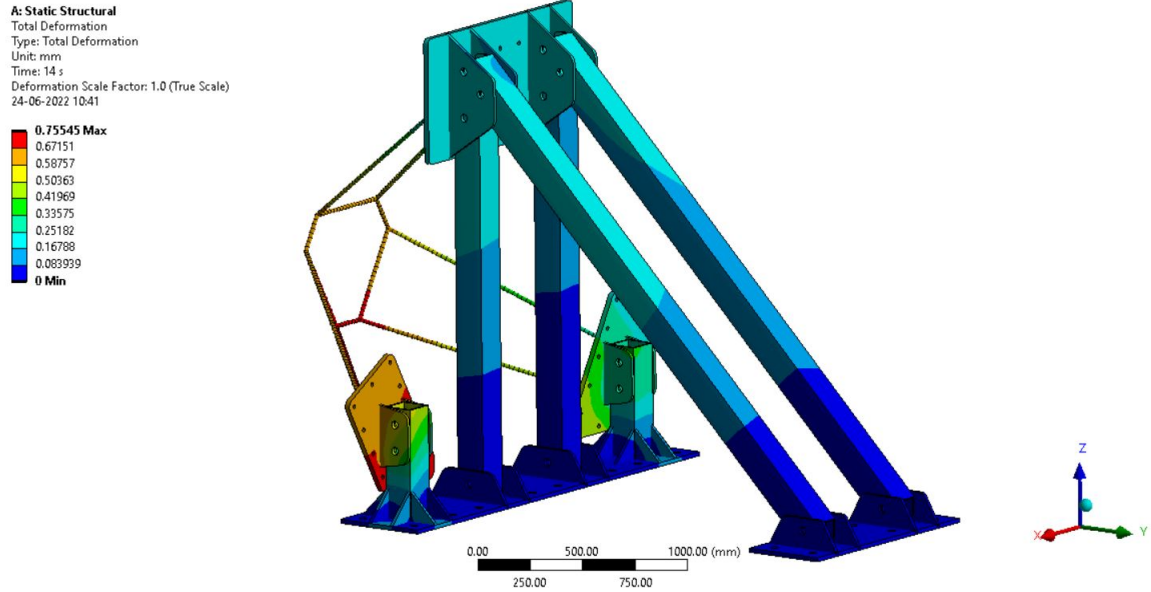


Fig. 24 Maximum displacement = 0.75545 mm

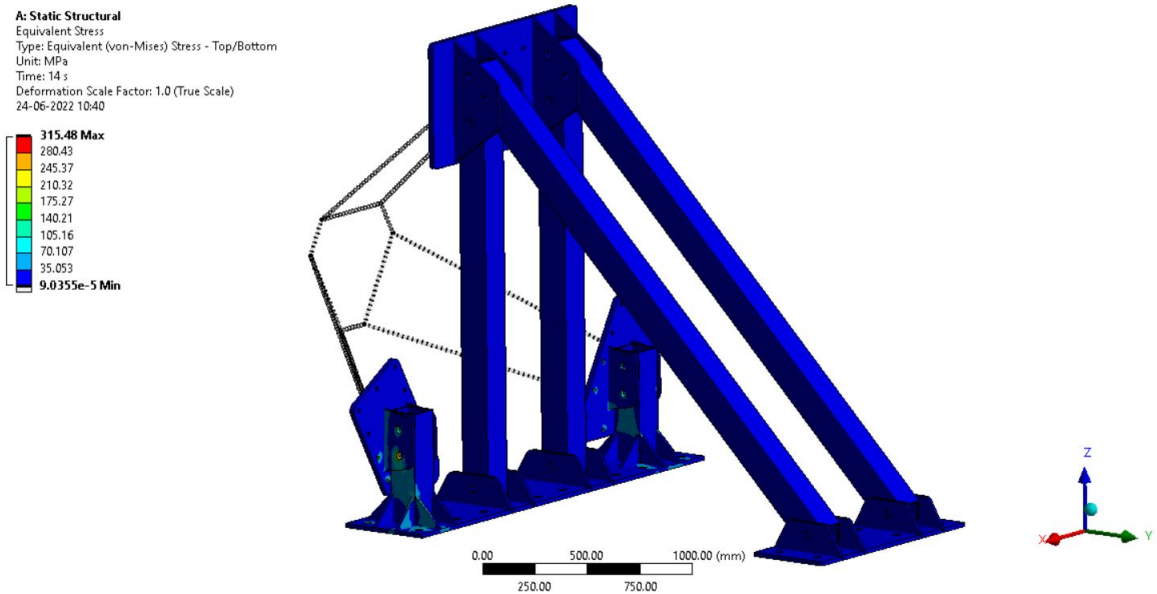


Fig. 23 Maximum Stress = 315.48 MPa

Results:

As noticed, the deformation obtained when the print head forces were resolved along the Hexapod resulted in significantly lower deformation. This is attributed to the fact that resolving forces along the Hexapod arms doesn't account for the moments generated at the bolting points. Hence, the first approach, i.e., case 1 in which both the weight of the print head and the reaction forces were scoped to the front of the hexapod was adopted to simulate further load cases.

Additionally, it was observed in the preliminary analysis, that the deformation for the side mounting brackets was greater than what is acceptable. Therefore, to increase stiffness, gussets were added to the side mounting brackets. This improved the stiffness of the side brackets.

2. Rotation about X-axis

Boundary Conditions:

- The Hexapod base is fixed to the ground.
- Fixed joints are assigned to bolted connections.
- The weight of the print head is modeled as a point mass, and a remote force scoped to the mounting brackets is used to simulate the weight of the Hexapod.
- The force exerted by the print head during operation, including the resistance to the motion of the print head and the normal reaction, is modeled as a remote force scoped to the top of the Hexapod. This force varies in direction as the print head rotates about the X-axis.

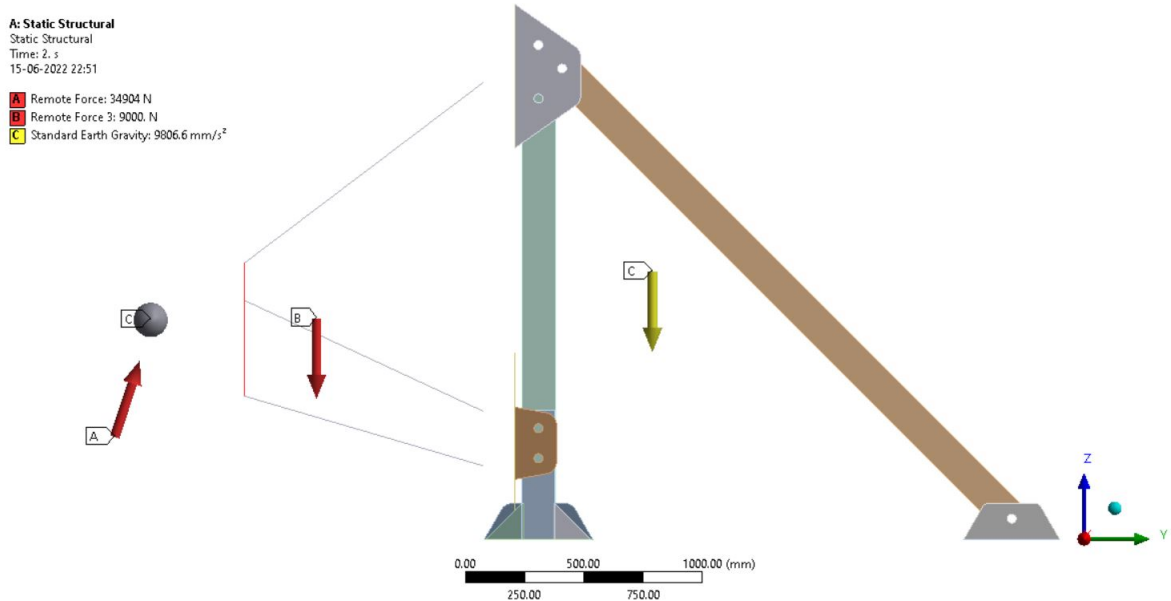


Fig. 25 Boundary Condition at Step 1

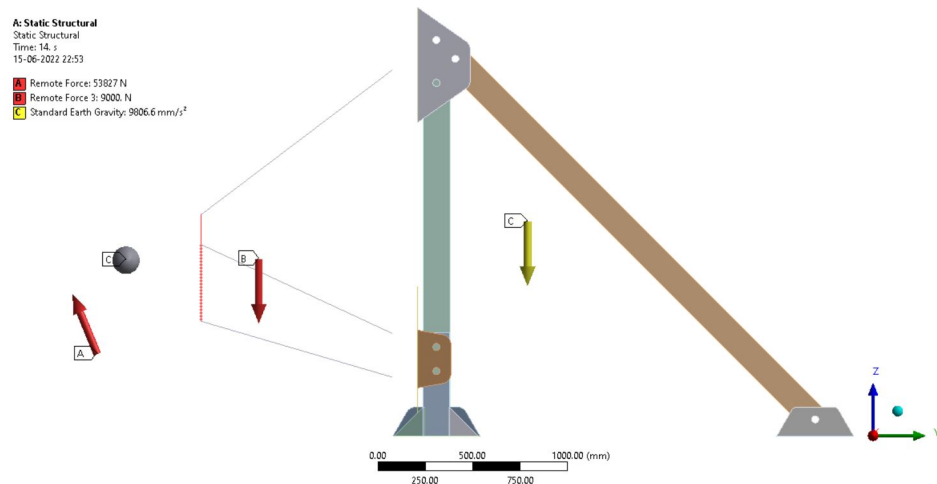


Fig. 26 Boundary Condition at Step 14

Results:

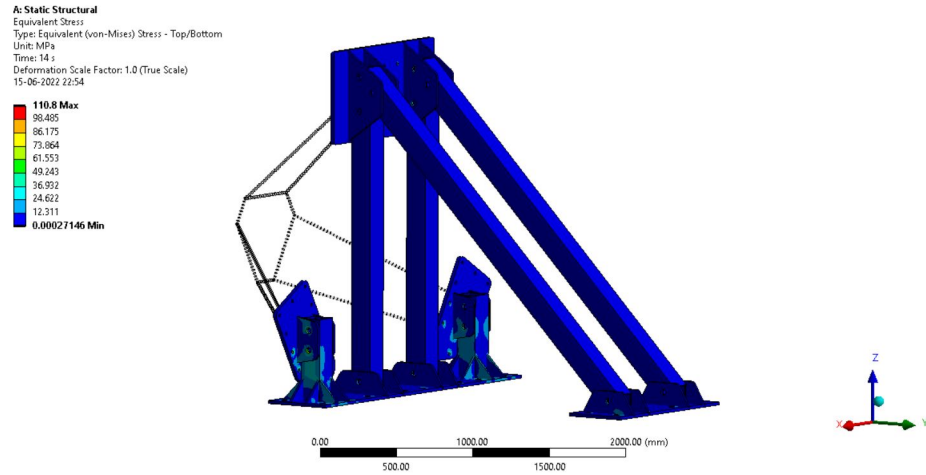


Fig. 27 Maximum Stress = 80.36 MPa

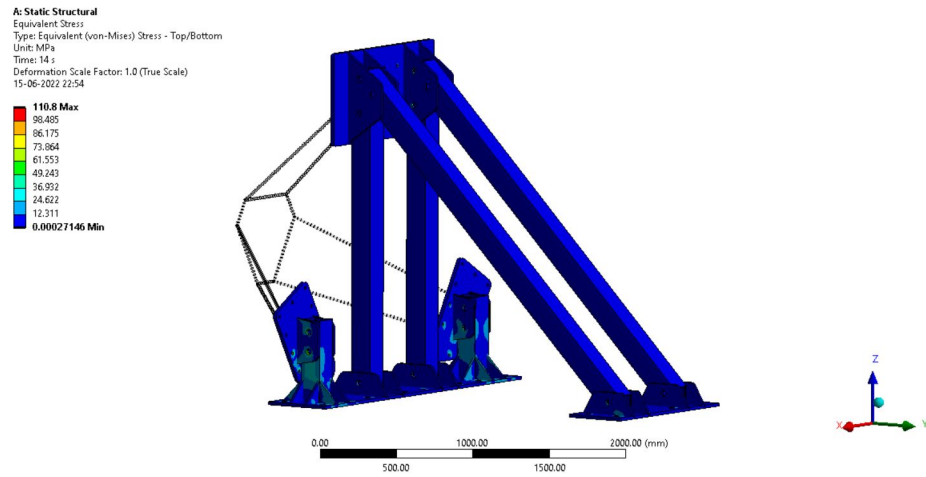


Fig. 28 Maximum displacement = 0.456 mm

3. Rotation about Y-axis

Boundary Conditions:

The boundary conditions are similar to those performed in the previous analysis. The only change is the force exerted by the print head, which is modified as it varies in direction when the print head rotates about the Y-axis.

A: Static Structural
 Static Structural
 Time: 2, s
 15-06-2022 20:50
A Remote Force: 36693 N
B Remote Force 3: 9000, N
C Standard Earth Gravity: 9806.6 mm/s²

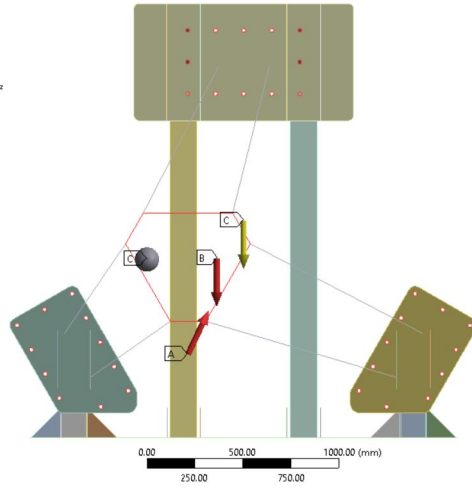


Fig. 29 Boundary Condition at Step 1

A: Static Structural
 Static Structural
 Time: 14, s
 15-06-2022 20:32
A Remote Force: 55039 N
B Remote Force 3: 9000, N
C Standard Earth Gravity: 9806.6 mm/s²

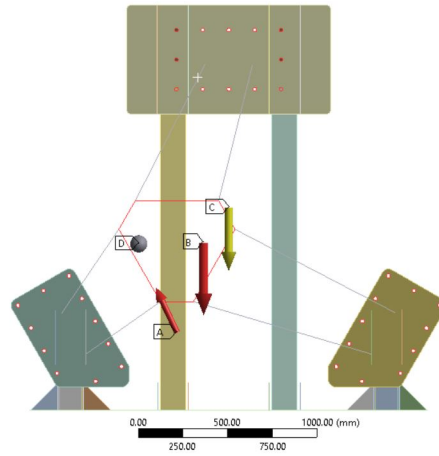


Fig. 30 Boundary Condition at Step 14

Results:

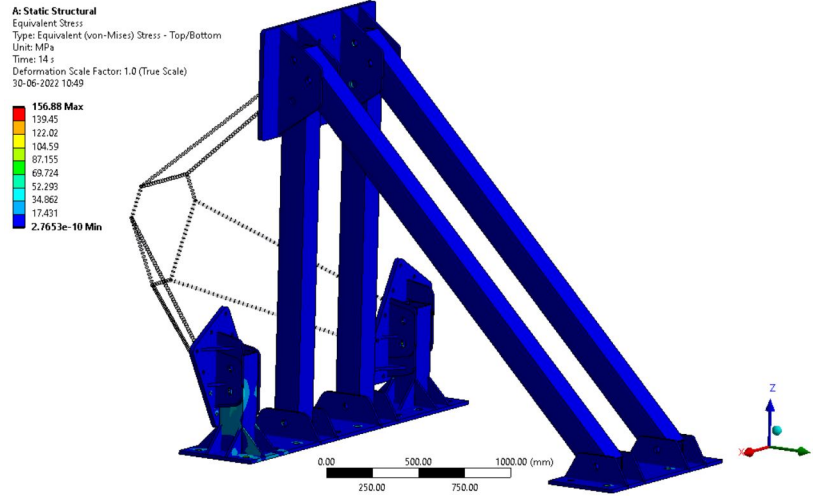


Fig. 31 Maximum Stress = 156.88 MPa

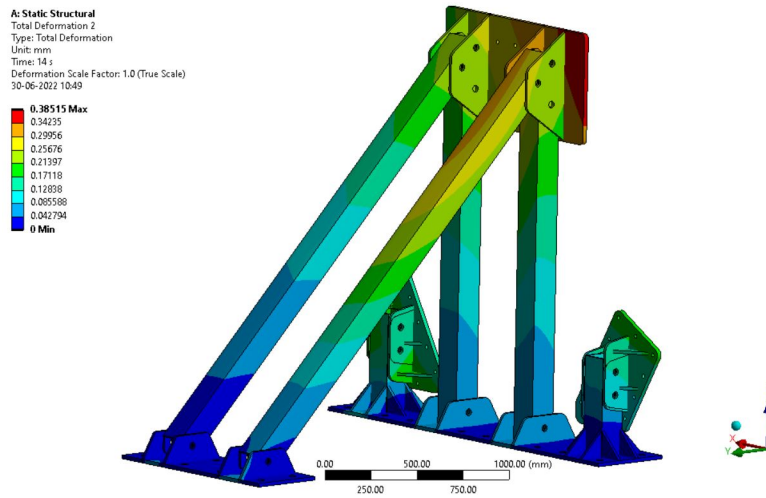


Fig. 32 Maximum displacement = 0.38515 mm

C. Analysis conclusions

From the analyses performed for various loading conditions, it was observed that the maximum deformation occurs on the lower bracket, while the maximum stress is observed close to the bolted connection between the square tubing and the stand. To address this, gussets are added between the base plate and the square tubing to increase its strength. Additionally, two bolts are used to mount the lower brackets instead of a single joint used previously.

Upon concluding these analyses, it was determined that re-orienting the rail such that it is parallel to the SP axes would be beneficial for expanding the workspace. However, re-orienting and raising the rail resulted in interference between the rail-feed system and the support structure. Therefore, the support structure was modified to eliminate this interference.

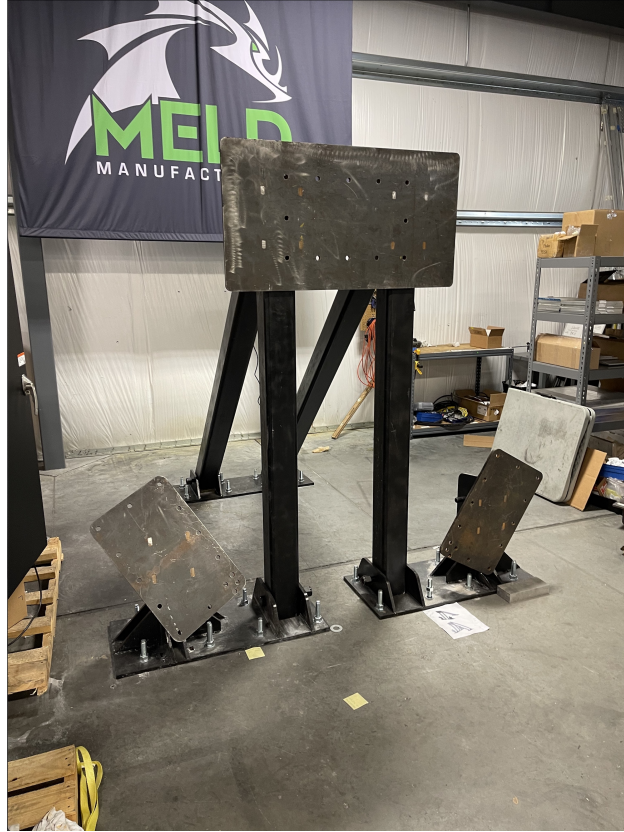


Fig. 33 Constructed support frame

IV. Workspace Analysis

Workspace Analysis took place using a Stewart platform with dimensions specified by SCT, placed relative to a high detail model of the target Rail. A transform from the end effector of the Stewart platform to the end of the spindle according to the latest CAD was also used. The dimensions used for the Stewart Platform model are thus:

Bottom Plate Thickness	0.188m
Top Plate Thickness	0.156m
Bottom Plate Joint Radius	0.960m
Top Plate Joint Radius	0.369m
Bottom Plate Joint Spacing	8.37 degrees
Top Plate Joint Spacing	22.23 degrees
Actuator Minimum Extension	1.074m
Actuator Maximum Extension	1.378m

Each rail STL based simulation used a normal-finding function to create a vector which is normal to each triangular face on the rail model, projected to be optimally in plane with the end effector home position. An example of these normal vectors is in fig 37.

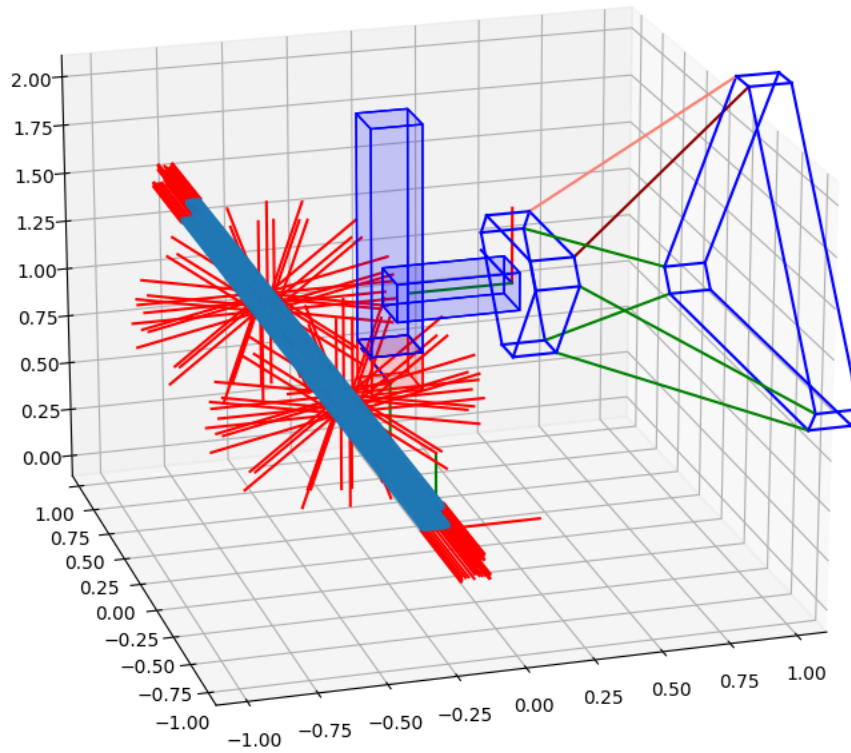


Fig. 34 Representation of Rail with surface normals projected in Red

A. Simulation Configuration 1

The first configuration is akin to the image presented in fig 17. The Hexapod head is placed so the rail moves laterally in plane with the surface of the Hexapod head in the home pose. Results with default positioning of the rail were significantly unsatisfactory. The Hexapod was able to reach the far side of the rail at up to 10 degrees off vertical, but it was not able to reach the near side of the rail, due to the limited travel of the linear actuators and the high degree of rotation and translation required on the part of the Hexapod to reposition the spindle. This is shown in fig 35.

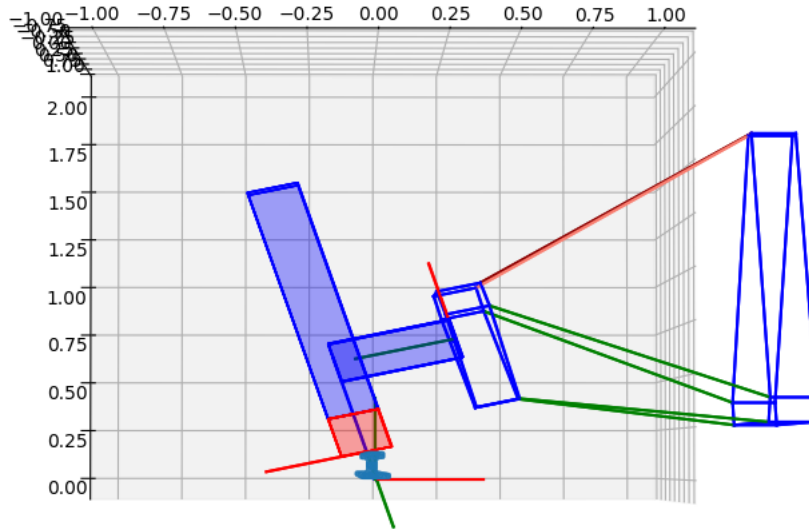


Fig. 35 Hexapod Reaching Rail Normal On Far Side Of Rail

In order to optimize the positioning of the rail system, a grid search was used which allowed the changing of the Z axis height of the Hexapod base relative to the rail (meters), the X axis distance (meters) of the Hexapod base relative to the rail, and the Y axis tilt of the Hexapod relative to the rail (degrees). The objective criterion for the grid search is the maximum number of rail surface normals achievable by the Hexapod without triggering a system fault.

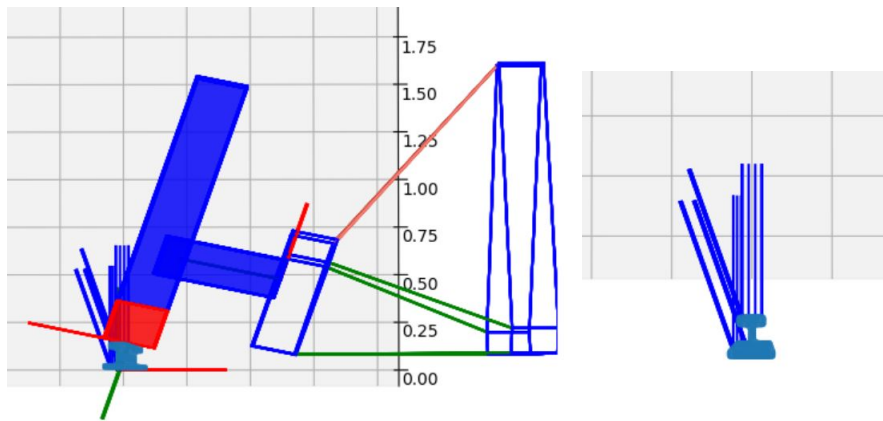


Fig. 36 Maximum Surface Normal Configuration of Hexapod On Rail Post Grid Search

The results of this grid search, though better than the initial condition, were less than satisfactory. The Hexapod could only hit the full top surface and the rail and nearly the full curvature of the far side of the rail. Fig 36A shows why the near side of the rail is infeasible - the Hexapod can not position its end effector low enough to gain the proper rotation of the spindle, with it being so far away from the Hexapod end effector. Fig 36B shows the maximum normals calculated by the grid search that the Hexapod could reach successfully. Note that the surface normals of the rail are not all encompassing, and this will be discussed later in the workspace analysis section.

Ultimately, simulation configuration 1 was not chosen due to poor access of the rail drive, necessitating the switch to the configuration shown in Simulation 2.

B. Simulation Configuration 2

Simulation configuration 2 reorients the rail such that the rail is perpendicular to the surface of the Hexapod end effector, aligned under the center line of the platform, separated by a gap of 0.762cm whilst the platform is in its home position. The theory is that this orientation of the rail results in significantly less demand for translation of the Hexapod end effector, improving the likelihood for success. This is shown in Figure 37. This was ultimately the chosen configuration.

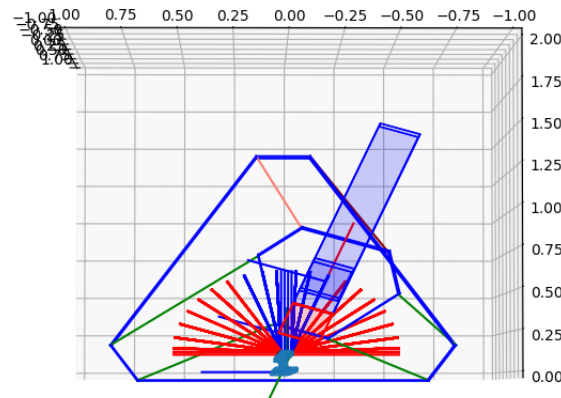


Fig. 37 Test Configuration Using Perpendicular Rail, Showing Hexapod Interfacing With Rail At +20 Degrees

Results of the simulation indicated that the Hexapod was able to achieve normal placement of the end effector to the rail at rotations of up to 20 degrees from vertical, filling operational requirements, as shown in 37. It is worth noting that the CAD file used to construct this rail is not perfect, and thus information is lost, so a secondary component to the simulation was used to determine rotational upper bound.

This secondary simulation replaces the rail with two points, positioned 67.5mm apart (the width of the rail), and the limits of rotation at those points were tested to see to what degree the platform could reach. This is shown in ???. Results from this test show the platform can reach ± 25 degrees rotation. However, this was only possible for a small band in the Hexapod's local Z axis of translation.

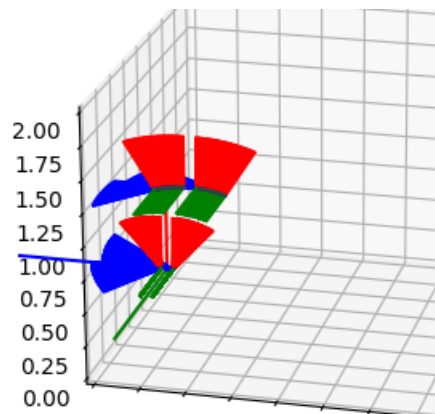


Fig. 38 Test Configuration Using Two Points At Rail Width

C. Workspace Visualization

Yet another simulation was performed in order to better understand the workspace limitations described above and better inform placement of the rail. This simple simulation was performed by modeling SCT's SP based on parameters extracted from the final CAD, linearly sampling the 6-dimensional workspace ($x, y, z, \theta_x, \theta_y, \theta_z$) at predefined mesh points, evaluating the inverse kinematics to determine the actuator lengths required to reach the pose (position and orientation) defined by the mesh point, and then comparing these computed lengths to the actual hardware limitations defined by SCT. If the pose did not violate actuator length constraints, the sample was considered valid. Numerous simulations of this type were executed while the mesh was refined at each step (i.e., window sizes were narrowed and the total number of samples was increased). After each simulation, large data structures including the position and orientation, required actuator lengths, and validity of each sample were saved. Although immensely helpful, it should be noted that this simulation was less rigorous than the previous simulations as it did not consider minor SP geometric details (e.g., the width of the plates or the angle offsets of the actuators at the plates). Due to this slight lack of rigor, it is believed that the workspaces defined within these structures are slightly over-constrained (some of the neglected details improve reachability).

Upon generating these workspace-containing data structures, they were then analyzed to ascertain the 3-dimensional *shape* of the workspace within the operational envelope. It is notable that, although the reachability ellipsoid's shape is closely approximated in this way, its scale is not necessarily accurate. In order to graphically illustrate the system's workspace via Cartesian Coordinates, the SP's workspace needed to first be transformed such that it captured the workspace of the printhead, and three degrees of freedom of the six-DOF workspace needed to be constrained based on expected/desired performance criteria. The most obvious constraint set involves the fixing of the three angle parameters - by considering only those samples defined by a set orientation, the valid *positions* of the printhead can be plotted. The inverse can also be accomplished; however, the results are less intuitive and thus precluded from this graphical analysis. Once three DOFs had been fixed, the valid workspace could then be plotted alongside the imported rail geometry. From these discrete samples, the boundaries of the reachability ellipsoids could be roughly inferred and, more importantly, the intersection of the of the workspace with the rail surface could be approximated.

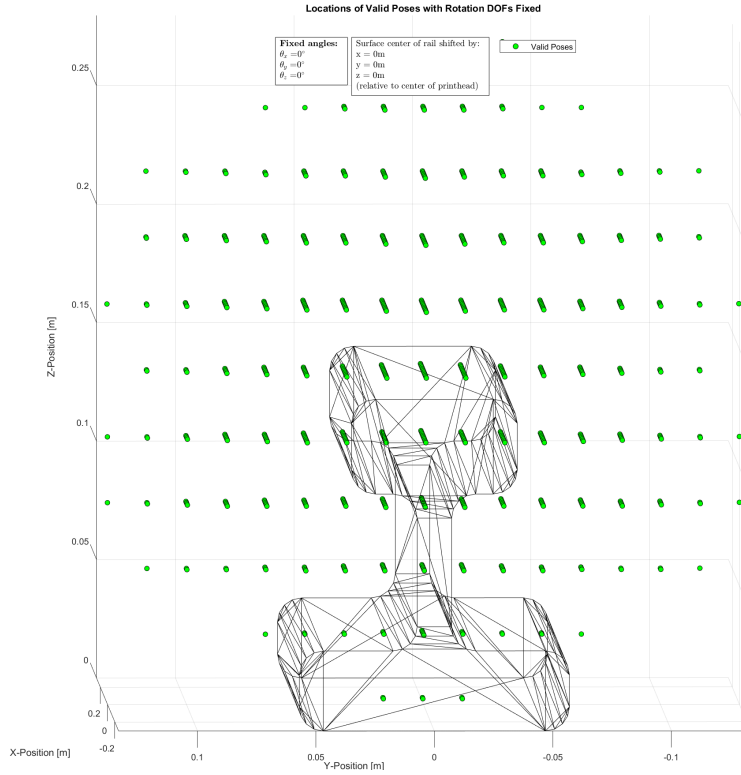


Fig. 39 Workspace cluster for $\theta_x = 0^\circ$.

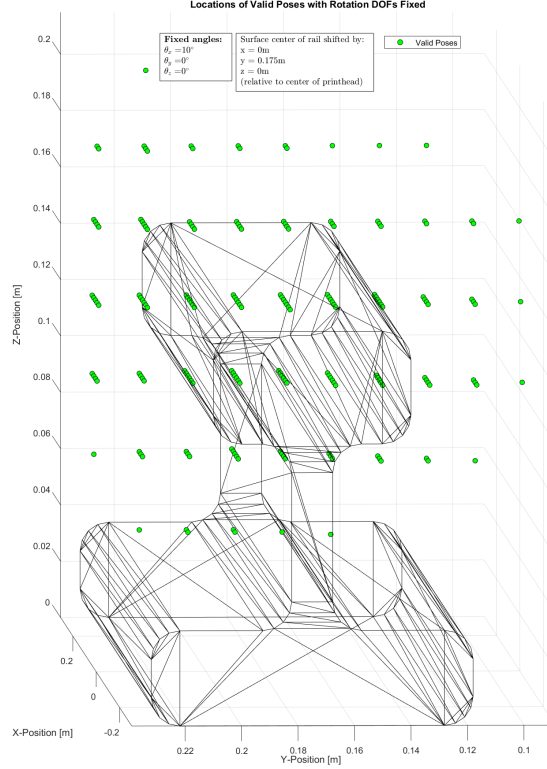


Fig. 40 Workspace cluster for $\theta_x = 10^\circ$.

D. Workspace Analysis Conclusions and Recommendations

Analysis indicates that rotating the rail such that it is perpendicular to the Stewart Platform plates significantly increases the range of motion available for working on surface normals.

Upon performing the above simulations with updated figures from SCT, it appears as if the system is adequately capable of reaching all desired surfaces on the rail if the rail is located 0.3 inches below the printhead at its home position.

V. Software Design

A. Structure

Another significant aspect of this project is software development. The FASER lab's responsibility entailed developing a control scheme capable of managing both the Hexapod and the Rail Mover, ensuring they adhere to specific printing paths provided by the MELD team. The control software operates on the Beckhoff PLC, which also functions as the Rail Mover motor controller, thus eliminating the requirement for an external host to control the system.

B. Rail mover

The Rail Mover is a single-degree-of-freedom robot controlled by a Beckhoff servo motor, which in turn is governed by a Beckhoff PLC. Connectivity to the Beckhoff PLC can be established by either a host machine or the PLC itself using the OPC-UA protocol. In the current configuration, the team employ the free Python "opcua" package running locally on the PLC as a host to communicate with the OPC-UA server. The Rail Mover code encompasses various functionalities, including setting the speed of the rail mover carriage and maneuvering the carriage to specified positions to ensure full autonomous operation during print. It's worth noting that the host machine currently connects to the PLC server through an anonymous connection; however, MELD may consider upgrading this in the future to enhance connection security.

C. Hexapod

The Hexapod is a large six-degree-of-freedom Stewart platform capable of being controlled in three modes. The first mode is the flight simulation mode, which controls the Hexapod's poses through velocity and acceleration data. The second mode involves controlling the Hexapod through X, Y, Z, roll, pitch, and yaw angles. The third mode enables control through the lengths of the six linear actuators. In this specific application, only the second control mode is utilized, as it offers the most intuitive way to convert the contour of the train track rail into the welding path that the Hexapod can read. Conveniently, the operator can also set the tip of the printing tool as the end-effector frame in the onboard Linux machine, so every motion command input into the Hexapod will be interpreted as the movement of that end-effector frame.

Communication between the host machine and the SCT Linux control system occurs through the EtherCAT protocol. The Hexapod control code consists of two main sections: the Xbox controller algorithm and the path-following algorithm. The Xbox controller script allows users to position the print head within the software-bounded work envelope freely. Meanwhile, the path script enables users to follow a specified print path. This printing motion is repeated endlessly until the entire top surface of the train track rail is covered, or the print material runs out.

D. Path following

To configure the path-following functionality in the control file, it is essential to have a CSV file containing raw data points of the train track rail. This raw file should include both the x and y locations for the top layer of the rail, as well as the angle normal to the surface at each specific location. With these data points, the path converter script can translate the x, y, and angle information into the corresponding x, y, z, roll, pitch, and yaw information that the Hexapod can interpret. The Hexapod then follows the print path to the endpoint, allowing the rail mover to progress a specified distance before reversing the sweeping motion to cover the next section. This process repeats until the entire top layer of the train track rail is printed.

E. Xbox Control Scheme

To securely operate the machine, an Xbox controller must remain connected to the host at all times. The Xbox controller serves as the control device for both the Hexapod and the rail mover. With the controller, an operator can manipulate the pose of the Hexapod in all six degrees of freedom, control the speed and position of the rail mover, and initiate or halt a print. These functions integrated into the controller allow the operator to complete the entire printing process without needing to interact with the host machine directly. Importantly, the controller also serves as an emergency stop mechanism. During operation, a user can promptly access and press the [B] button on the Xbox controller to halt any potentially hazardous actions performed by the Hexapod and the rail mover. Detailed instructions regarding the buttons on the controller and their associated functions can be found in Appendix A.

VI. Testing Results

More than 100 hours of testing have been conducted to assess the reliability and print quality of this system. The Hexapod must achieve three primary goals to be considered qualified. Firstly, it must isolate one coordinate movement from the other two. In a particular test, a pen was affixed to the print tool, and the machine was translated in one coordinate direction at a time. The Hexapod successfully drew straight lines in all x, y, and z directions, indicating its ability to produce clean motion even with slight alterations to its base geometry during assembly.

Secondly, the Hexapod must rotate freely in yaw, pitch, and roll angles while maintaining the translation value of the print tool in its working envelope. During testing, the print tool remained stationary atop the tip of a pen as an operator rotated the Hexapod in all three angles. Throughout the test, the print tool maintained its position without leaving or colliding with the pen tip, demonstrating excellent motion accuracy across all three rotation axes.

Subsequently, linear print tests were conducted on a train track rail to assess the rail mover and Hexapod's ability to maintain their poses under load. The rail mover motor sustained its speed with less than 50 percent of its peak torque rating, while the Hexapod achieved a maximum offset angle of 18 degrees during the tests, showcasing this system's capability under extreme conditions. Lastly, a sweeping print test was conducted to validate the system's ability to cover the complete top surface of the train track rail. The team successfully deposited material on top of the rail up to 12 degrees on each side, with the print results of one test shown below.

Upon evaluating the Hexapod's performance, it becomes apparent that the print quality consistently improves as

machine feeds and speeds are optimized. Notable enhancements to the system's rigidity and mounting have substantially reduced operational vibrations induced by spindle load, resulting in performance comparable to conventional ball screw table systems. As depicted in the accompanying figure, the machine adeptly navigates the rail contour while maintaining stable print height and feed rate, emphasizing the importance of heightened rigidity in achieving superior print quality.



Fig. 41 Print result with sweeping motion

VII. Conclusions and Recommendations

The VT FASER Lab collaborated with the MELD team by providing assistance in several key areas, including calculating the working envelope of the Hexapod, designing a single-degree-of-freedom rail mover system, constructing a supporting frame for the Hexapod, and developing software to maneuver and print with the rail mover and Hexapod systems using a given path file. The FASER lab completed the design, manufacturing, and testing of these tasks, enabling the Rail Mover, Hexapod systems, and print head to collaborate in printing objects within all six degrees of freedom.

While the experiment demonstrates that the hardware developed by the FASER team can effectively deposit materials on top of train track rails, there are numerous opportunities for further improvement. Primarily, the current system operates in an open-loop manner, meaning no print or force information is fed back into the control system to enhance print quality. Consider one of the most critical parameters, the distance between the bottom of the print head and the top surface of the rail. Presently, operators must manually lower the print head to make contact with the rail and set this height as a constant value throughout the entire print. However, this approach can lead to inconsistencies. The top surface geometry of train track rails may vary due to wear and rust accumulated over years of heavy use, resulting in differing print quality between prints. Therefore, implementing a feedback control system based on existing data, such as print head temperature, linear actuator current, or the integration of a laser profiler, would be an ideal enhancement for the future printing system.

VIII. Appendices

A. Xbox controller layout



Fig. 42 First Layer Control of the Xbox Controller

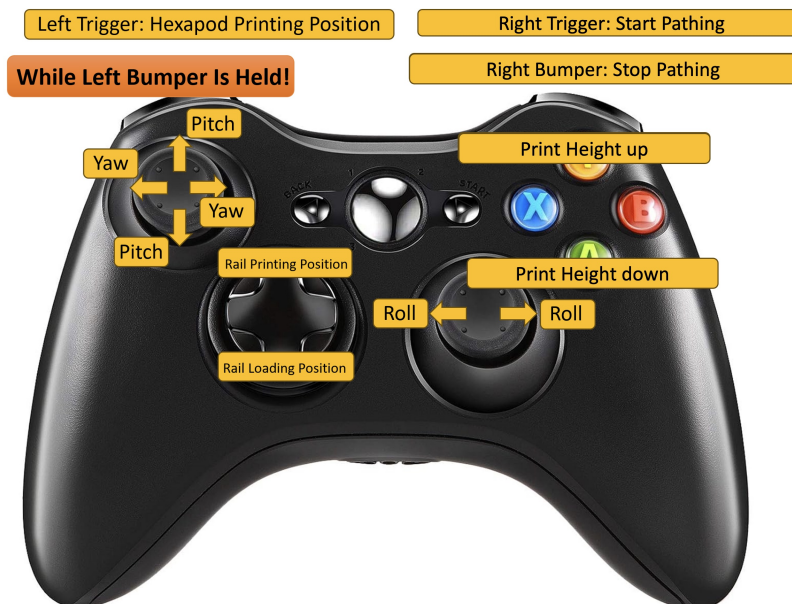


Fig. 43 Second Layer Control of the Xbox Controller

B. Operation Procedures

- Save a CSV path file in the format of [x, y, roll] angle in the "SP" folder.
- Identified the side-by-side offset of the rail relative to the Hexapod's home position and enter them in the lines 42 and 43 of "sp path converter2.py".
- Run "sp path converter2.py" to generate a "x y z roll pitch yall" path file that the Hexapod can read.
- Edit file "sp path test.py". Enter the rail position as the starting location for the print, then enter the step length in lines 89 and 91.
- Run "sp path test.py". Press [start] to initialize the operation and press [X] to start the control.
- Press [left bumper] + [left trigger] to bring the Hexapod tool head to the midpoint of the print path.
- Turn on the spindle. Use [left bumper] and [A] to bring down the print head to the proper height. You will need to repeat this process multiple times since the increment with each press is set to be extremely small.
- Press [left bumper] + [right trigger] to start the print pathing.
- After the print is finished, use [left bumper] and [Y] to bring up the print head then use [left bumper] and [right bumper] to turn off the pathing.