Cosmic Capstone Challenge 2026

The Miners-Track 1

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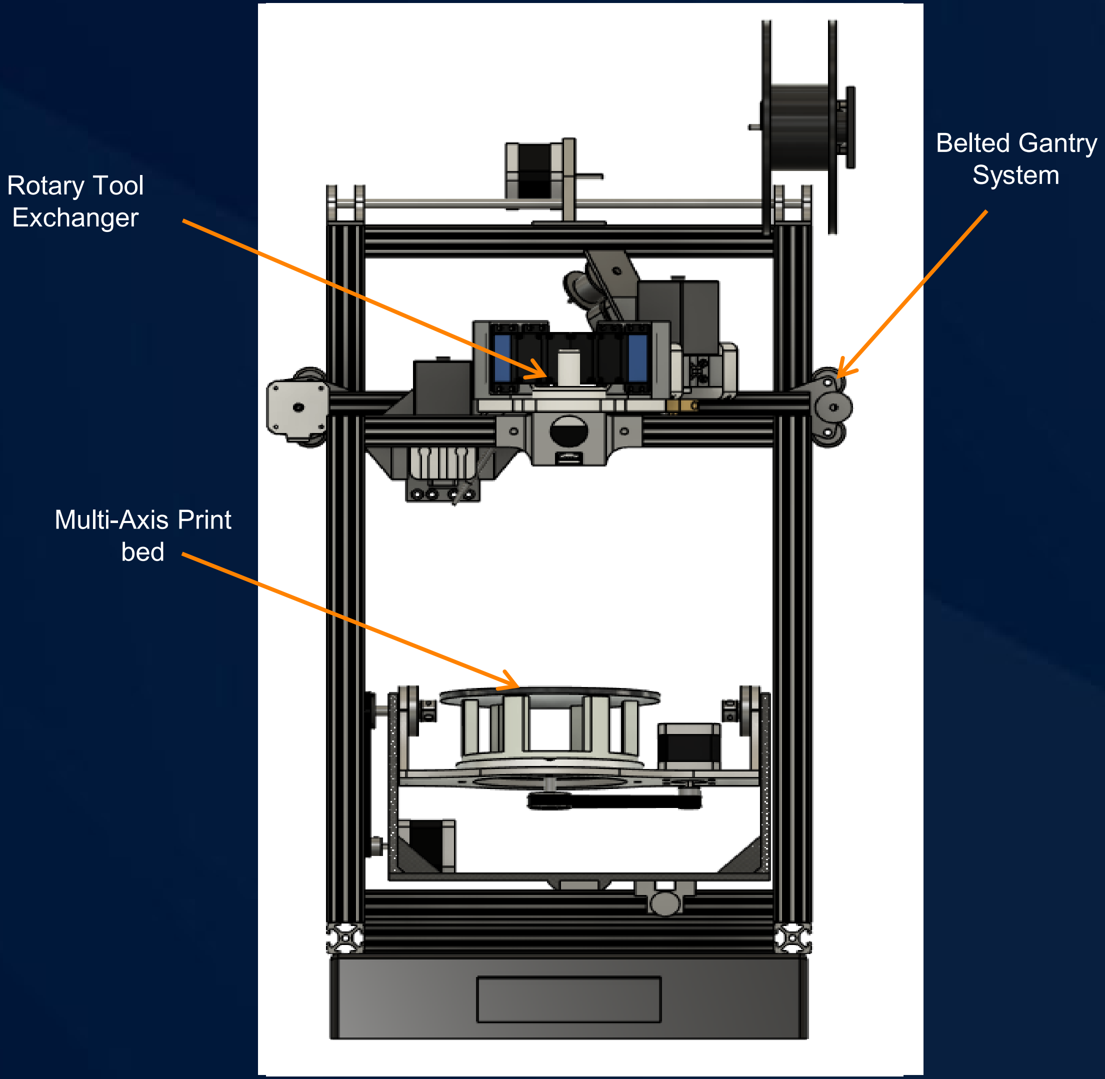
Mission Objective

- Develop a compact, autonomous fabrication payload for the Bosun's Locker that integrates multi-functional manufacturing processes, including 3D printing, soldering, and wire embedding
- Ensure spaceflight-ready performance through compliant materials, automated tool-changing, advanced sensing and control, validated operation via modeling and subsystem testing
- The system was designed using commercially available parts for maintainability and ease of assembly



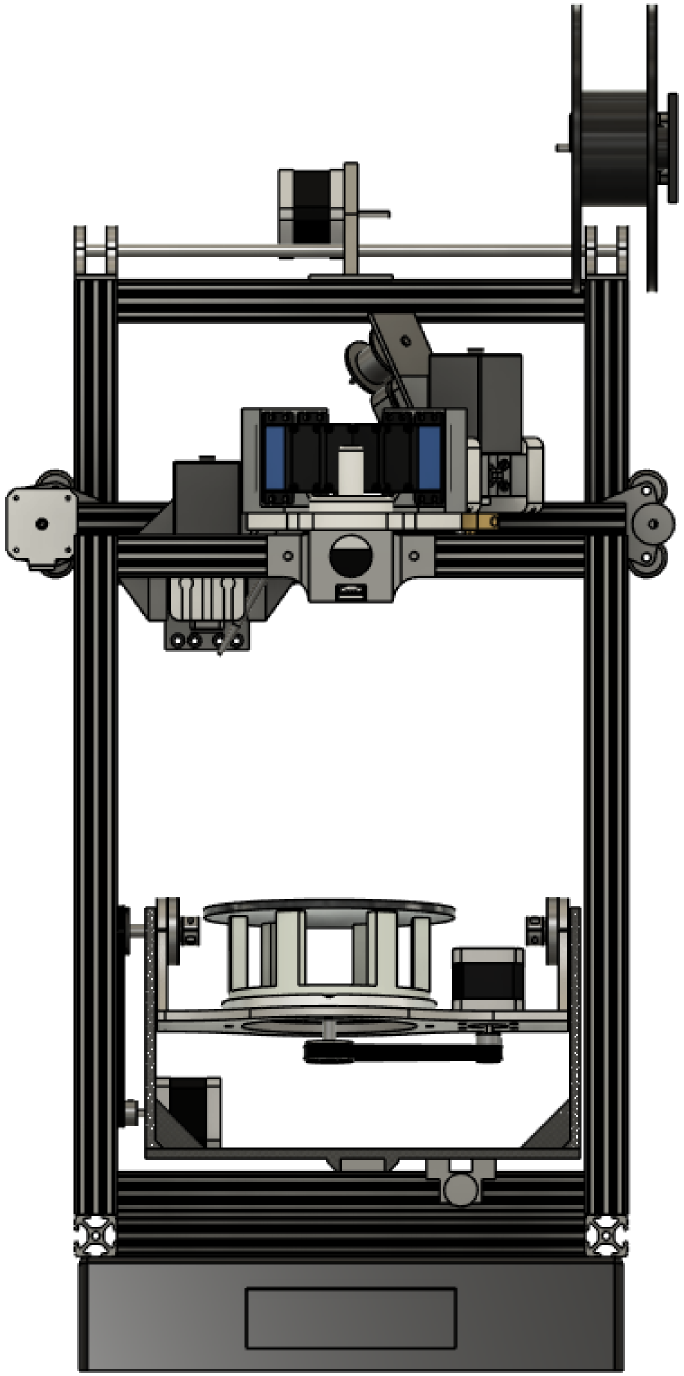
Bosun Locker with integrated subsystems

Problem and Value Proposition

- The model is a single, compact payload replaces multiple specialized tools by integrating 3D printing, soldering, and wire embedding in one system. It can create a variety of parts in a spacecraft

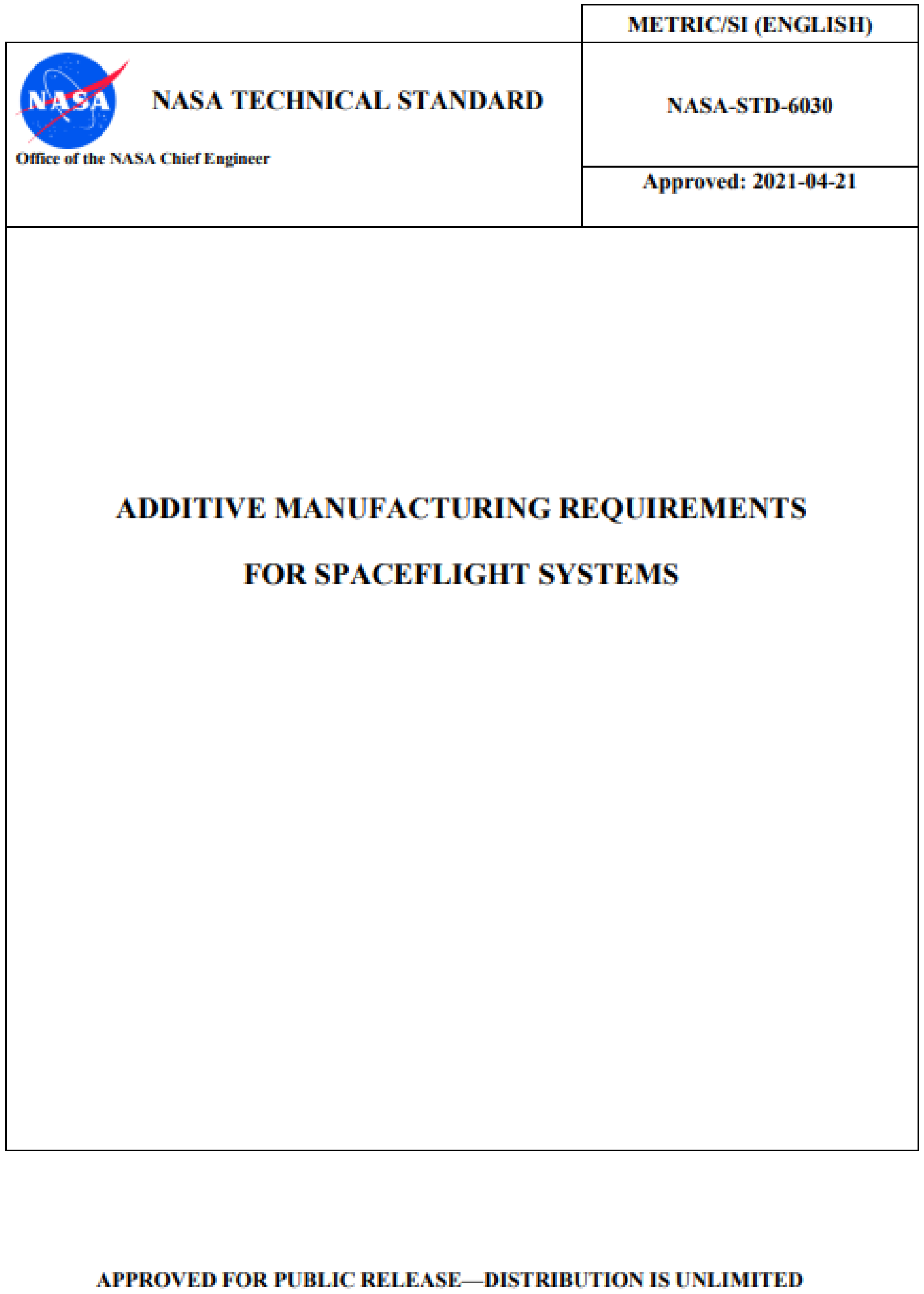
- It can extend the operational lifespan of satellites and reduces long-term orbital waste

- **Target Market: Satellite Manufacturers and Operators, Commercial Space Organizations, Government Space Agencies**



Innovation

- Use of space-grade polymers like PEEK and ULTEM 9085 ensures high thermal stability and structural reliability in vacuum environments
- Minimizes need for human oversight due to the semi-autonomous sequences that the locker uses
- Adheres to NASA-STD-6030 for additive manufacturing and material standards
- While most systems 3D print, this Bosun locker is a multifunctional hybrid that integrates soldering and wire embedding in one sequence



METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

NASA-STD-6030

Office of the NASA Chief Engineer

Approved: 2021-04-21

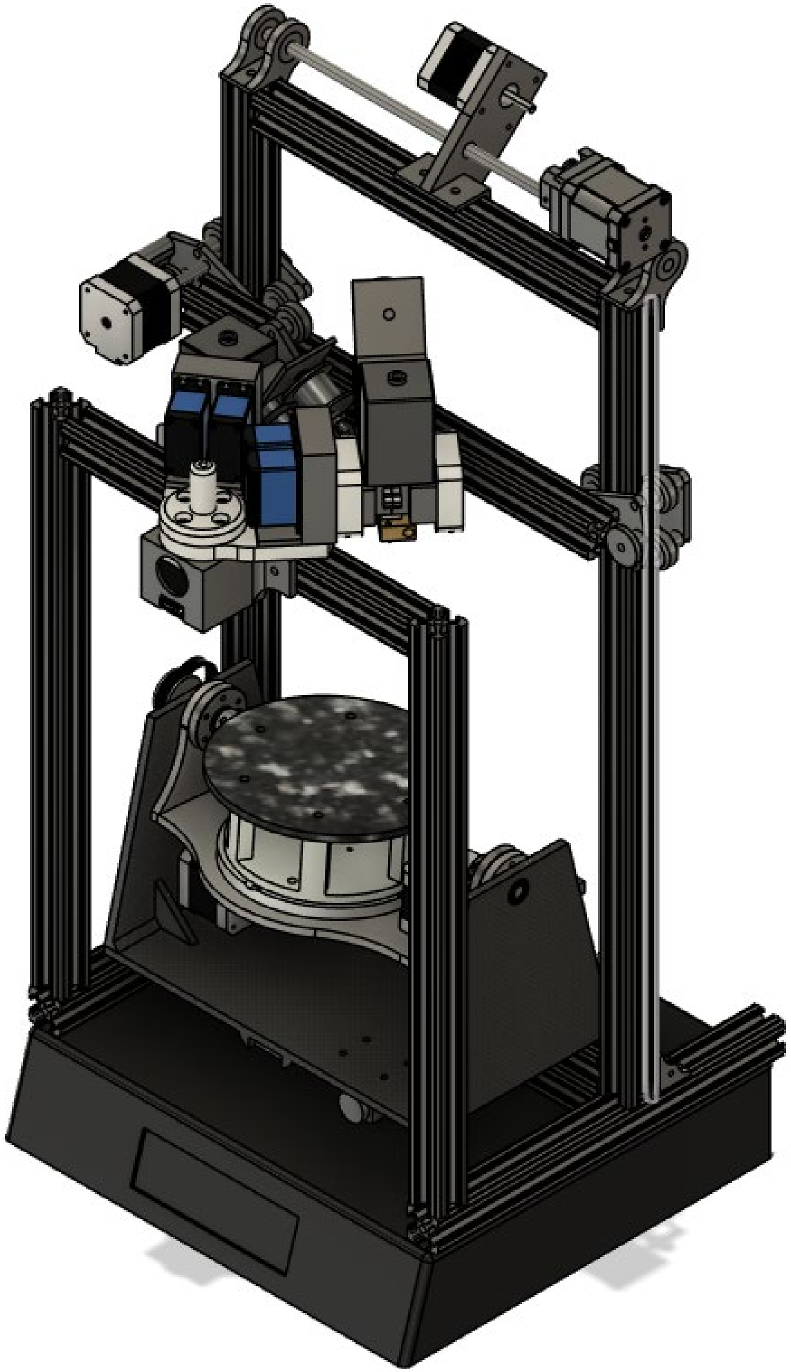
ADDITIVE MANUFACTURING REQUIREMENTS

FOR SPACEFLIGHT SYSTEMS

APPROVED FOR PUBLIC RELEASE—DISTRIBUTION IS UNLIMITED

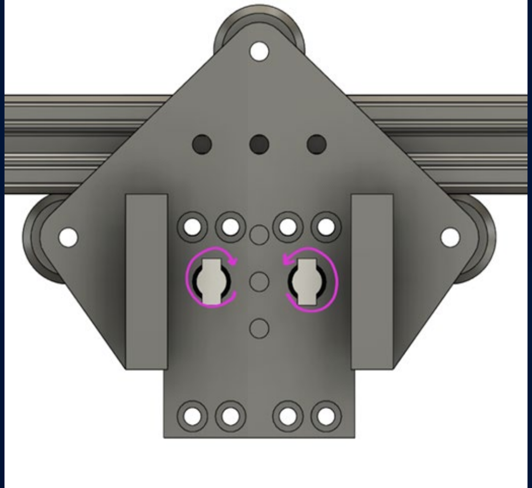
System Architecture

- The system integrates multiple subsystems into a single compact payload
- Key components include the gantry system, print bed, and tool exchanger
- Sensors and control systems enable safe and autonomous operation

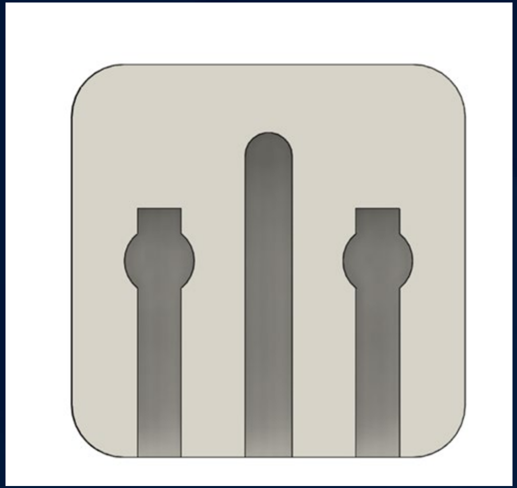


Concept of Operations

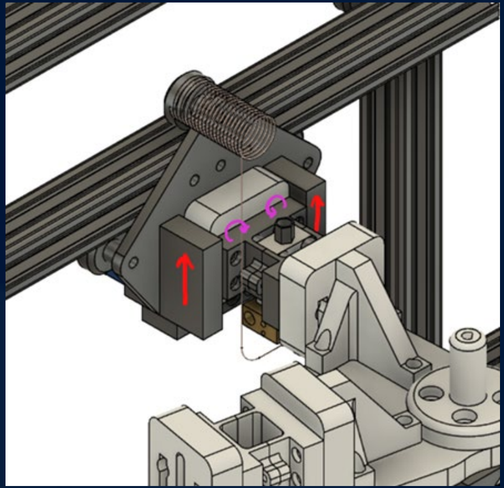
1. Rotate Keys



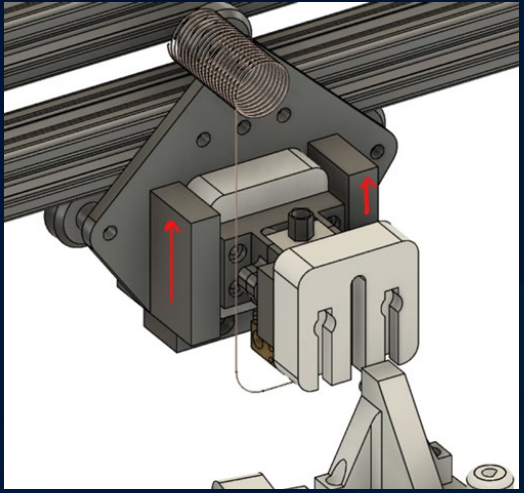
2. Align properly so it slides into holder



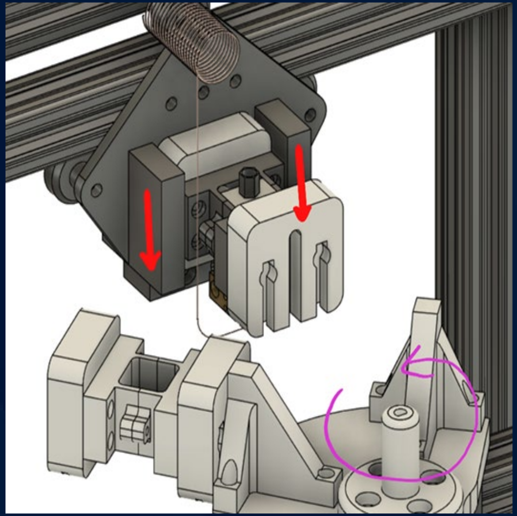
3. Move gantry to ready position and lock keys



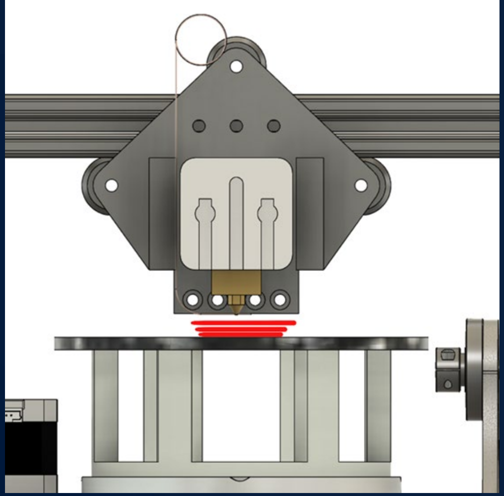
4. Move gantry upward to release from tool exchanger



5. Move gantry downward out of the way of tool exchanger

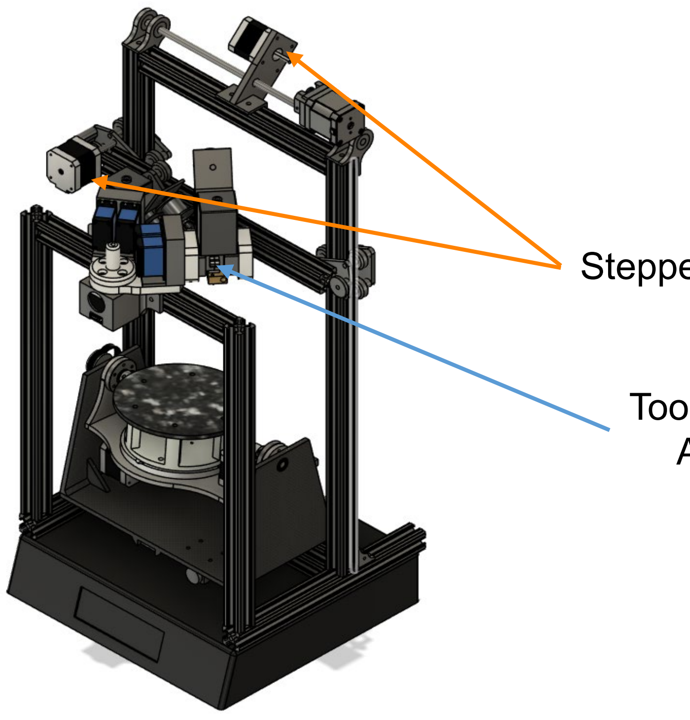


6. Begin desired tool actuation

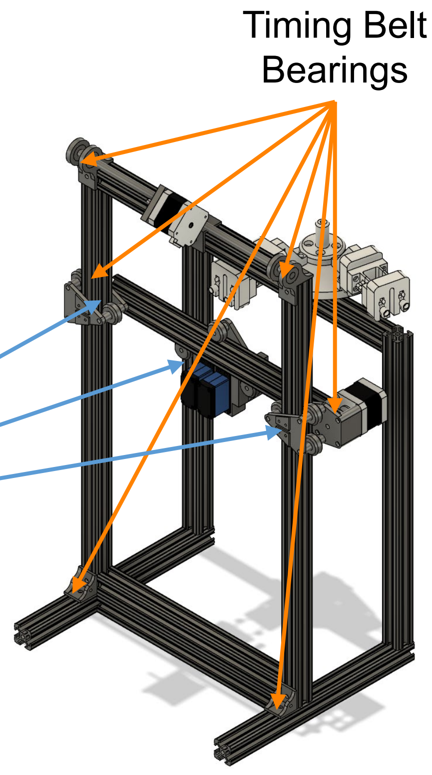


Gantry System

- Belted vertical and horizontal axes allow for movement of the toolhead with one motor per translational axis
- The rotary tool swapper was positioned to reduce collision risk with locker and gantry



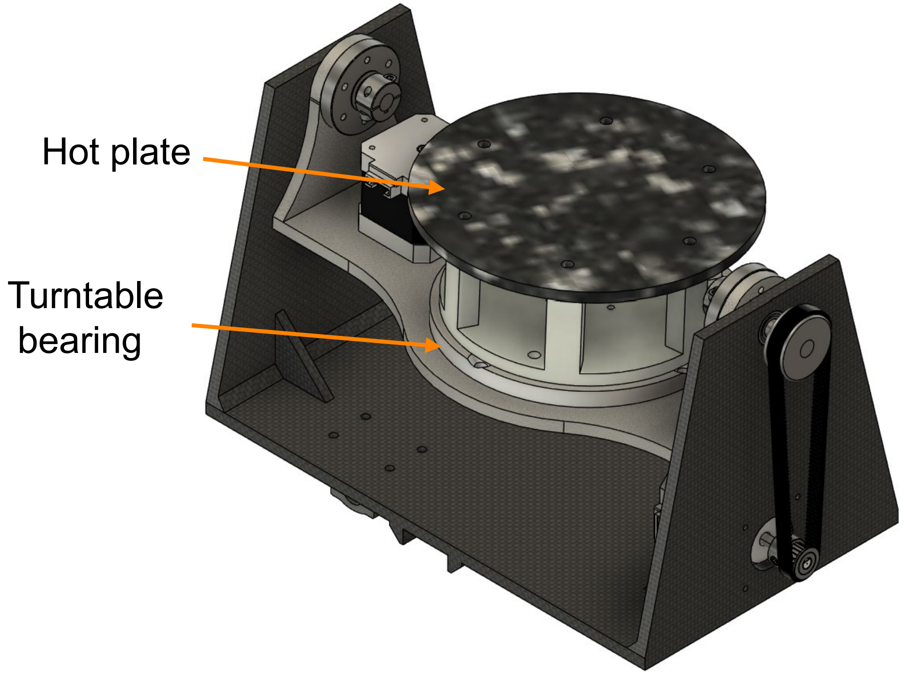
Front Isometric View of Gantry



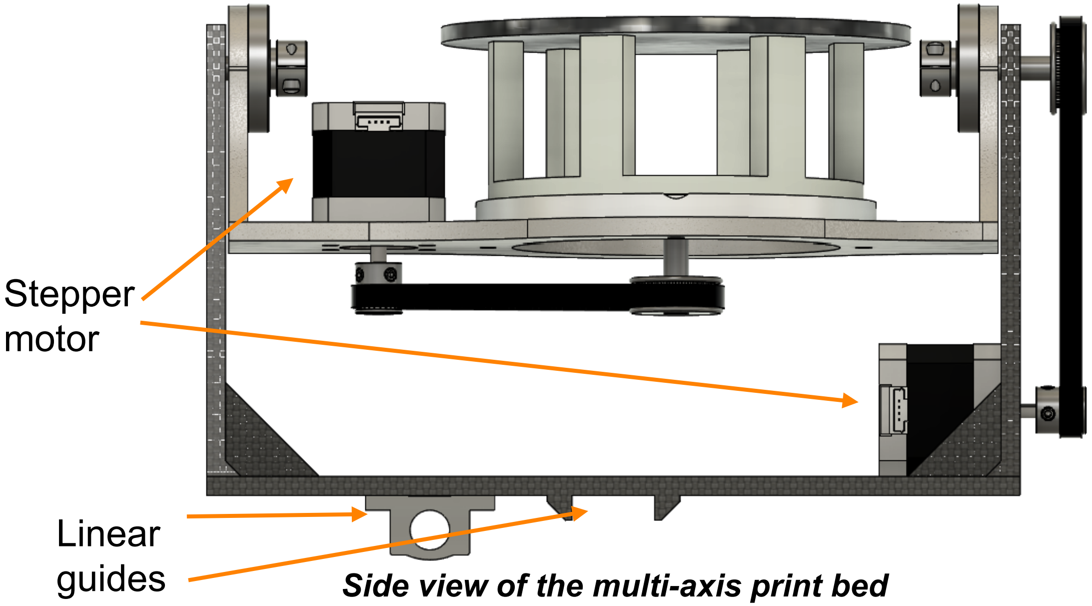
Back Isometric View of Gantry

Multi-Axis Print Bed

- The multi-axis print bed is designed to reduce or eliminate support material for overhangs
- Two pulley-driven stepper motors provide the bed with two rotational degrees of freedom
- Guide rails under the bed carriage add one translational degree of freedom
- Combined with the printer’s existing X/Z motion, the system achieves **five total degrees of freedom**: three translational and two rotational



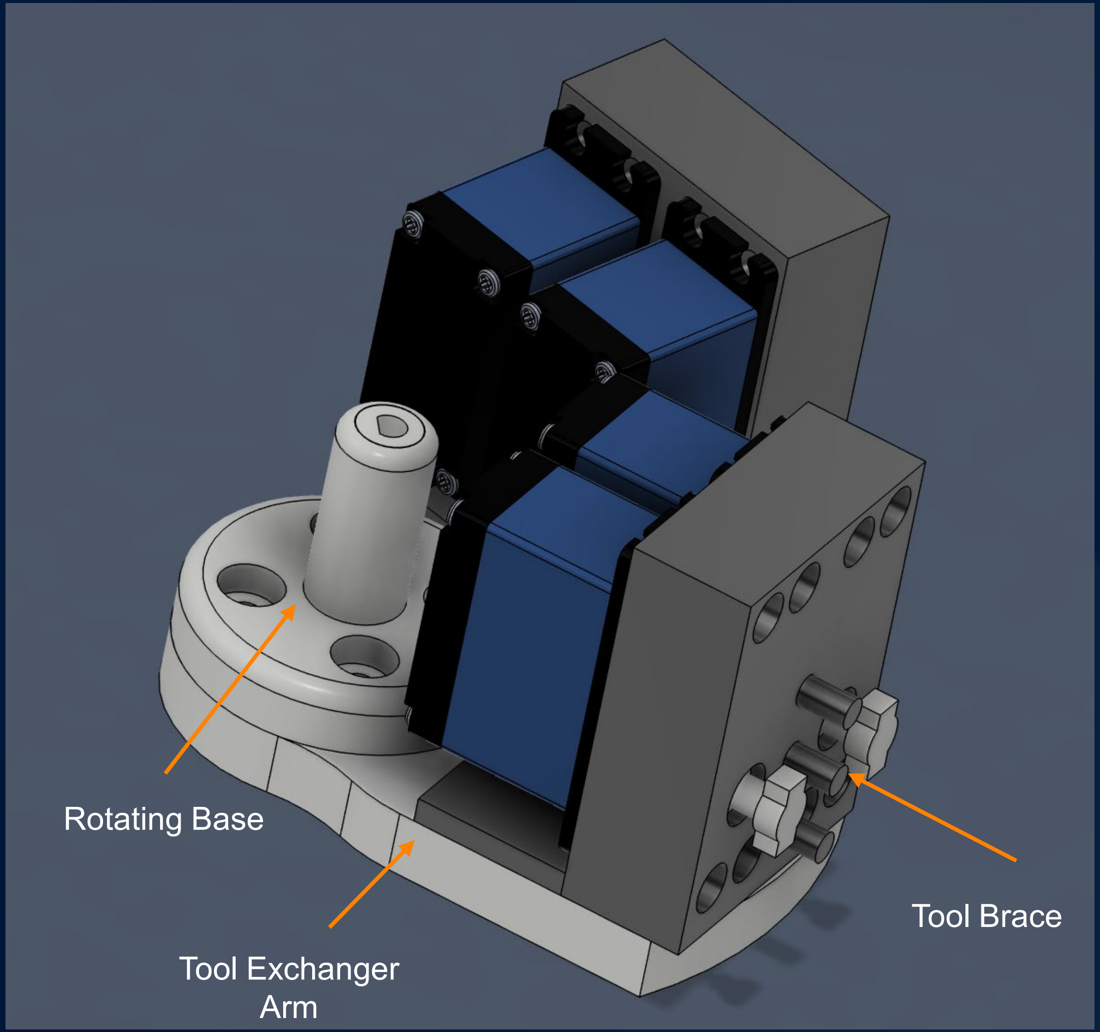
Isometric view of the multi-axis print bed



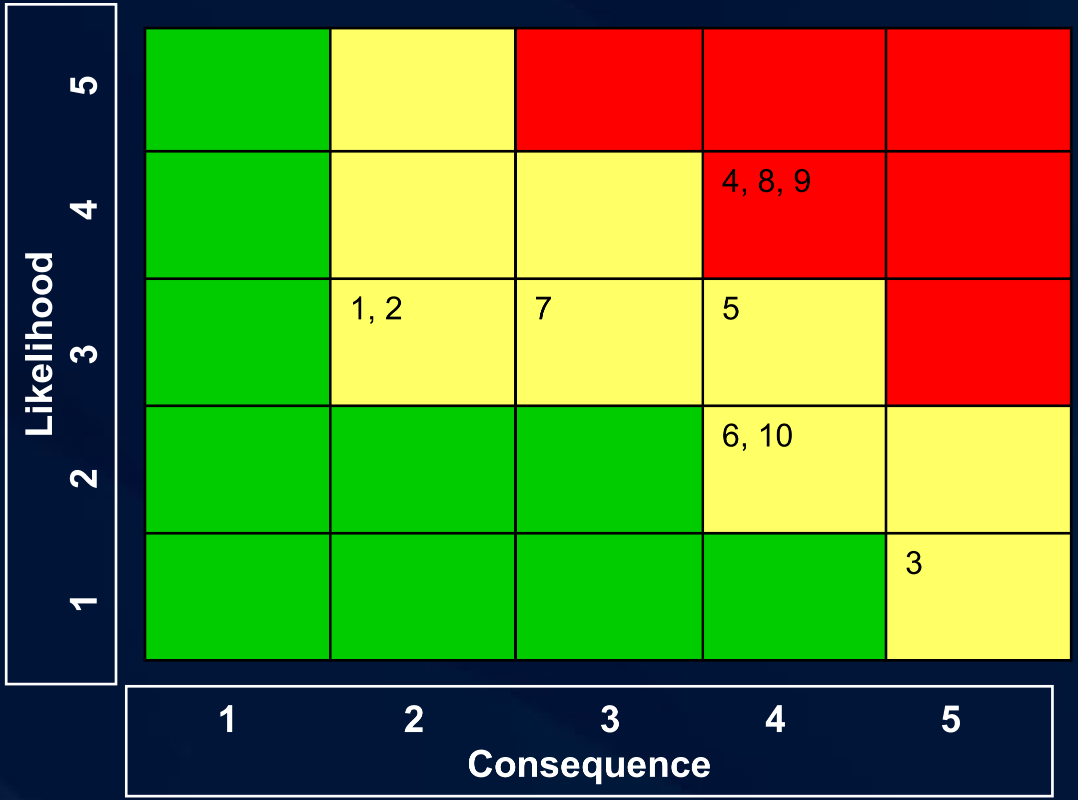
Side view of the multi-axis print bed

Rotary Tool Exchanger

- The rotary tool exchanger securely stores the locker's tools while providing a smooth, swap-ready mechanism for quick and efficient tool changes
- The system integrates with the Belted X platform and uses a keyed locking mechanism to secure each tool in place.



Risk Assessment



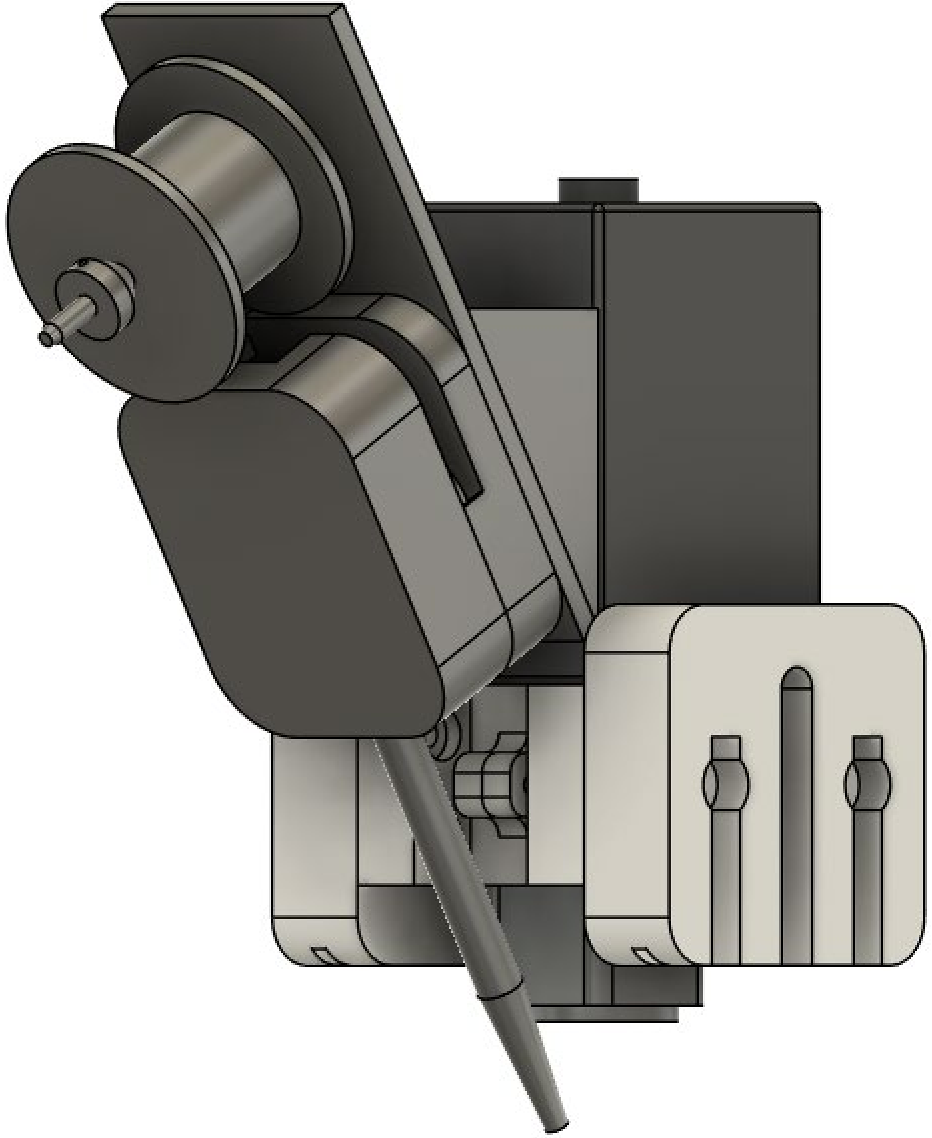
Likelihood					
5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥 4, 8, 9	🟥
3	🟩	🟨 1, 2	🟨 7	🟨 5	🟥
2	🟩	🟩	🟩	🟨 6, 10	🟨
1	🟩	🟩	🟩	🟩	🟨 3
Consequence	**1**	**2**	**3**	**4**	**5**

Criticality	**L x C Trend**		**Approach**
🟥 High	⇩	Decreasing (Improving)	M - Mitigate
🟨 Med	⇧	Increasing (Worsening)	W - Watch
🟩 Low	⇨	Unchanged	A - Accept
	☐	New Since Last Period	R - Research

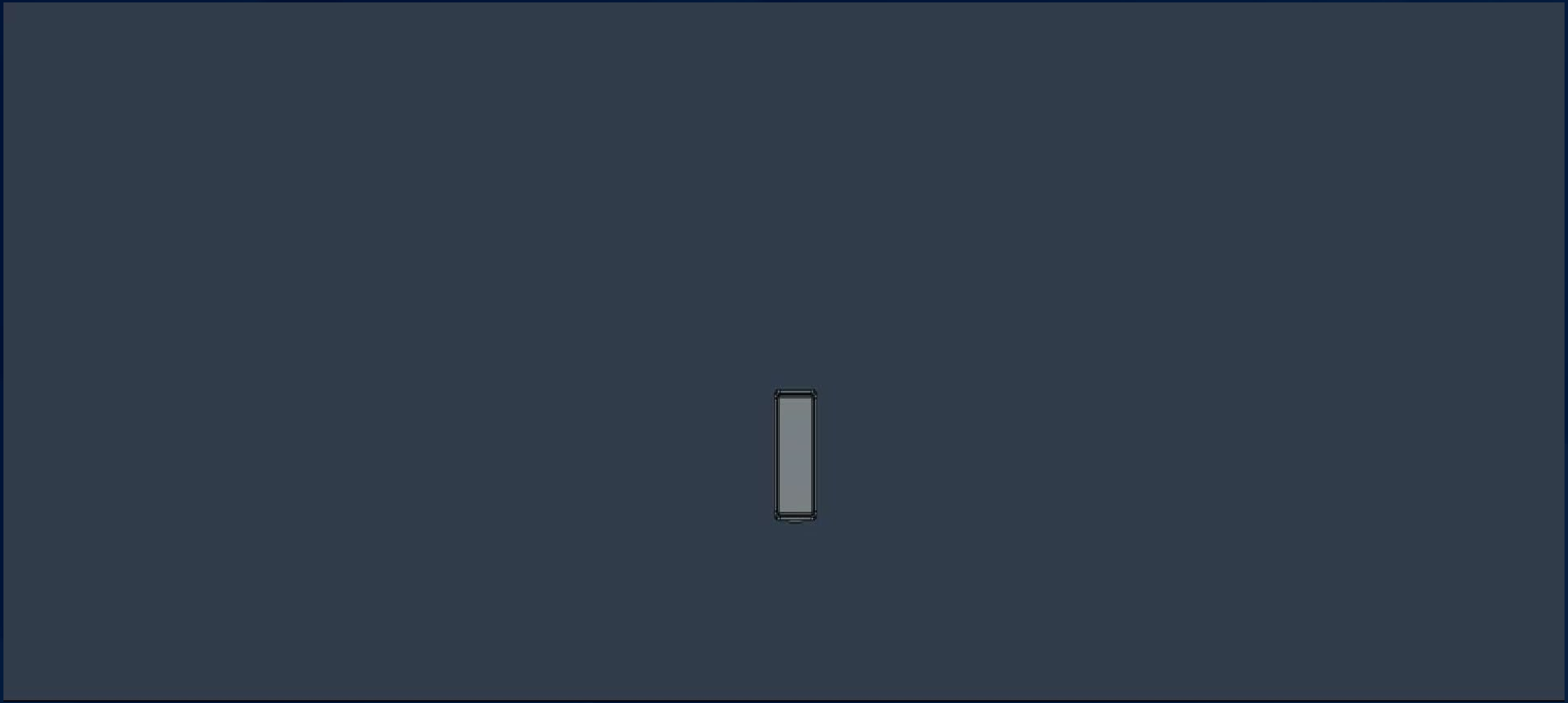
Rank	Trend	Risk ID	Approach	Risk Title
1	☐	1	M	Solder Temperature High (300°C+)
2	☐	2	M	Laser module is overheating
3	☐	3	W	Laser Scattering
4	☐	4	M	Laser Burning
5	☐	5	A	Wire Stripping and Grip Loss
6	☐	6	M	Optical Kickback
7	☐	7	M	Thermal Creep in Feed Mechanism
8	☐	8	M	Internal Gantry Contamination (Debris)
9	☐	9	M	Solder Does Not Stick (Wetting Failure)
10	☐	10	M	Mechanical Binding of the Sealed Locker

Risk Analysis

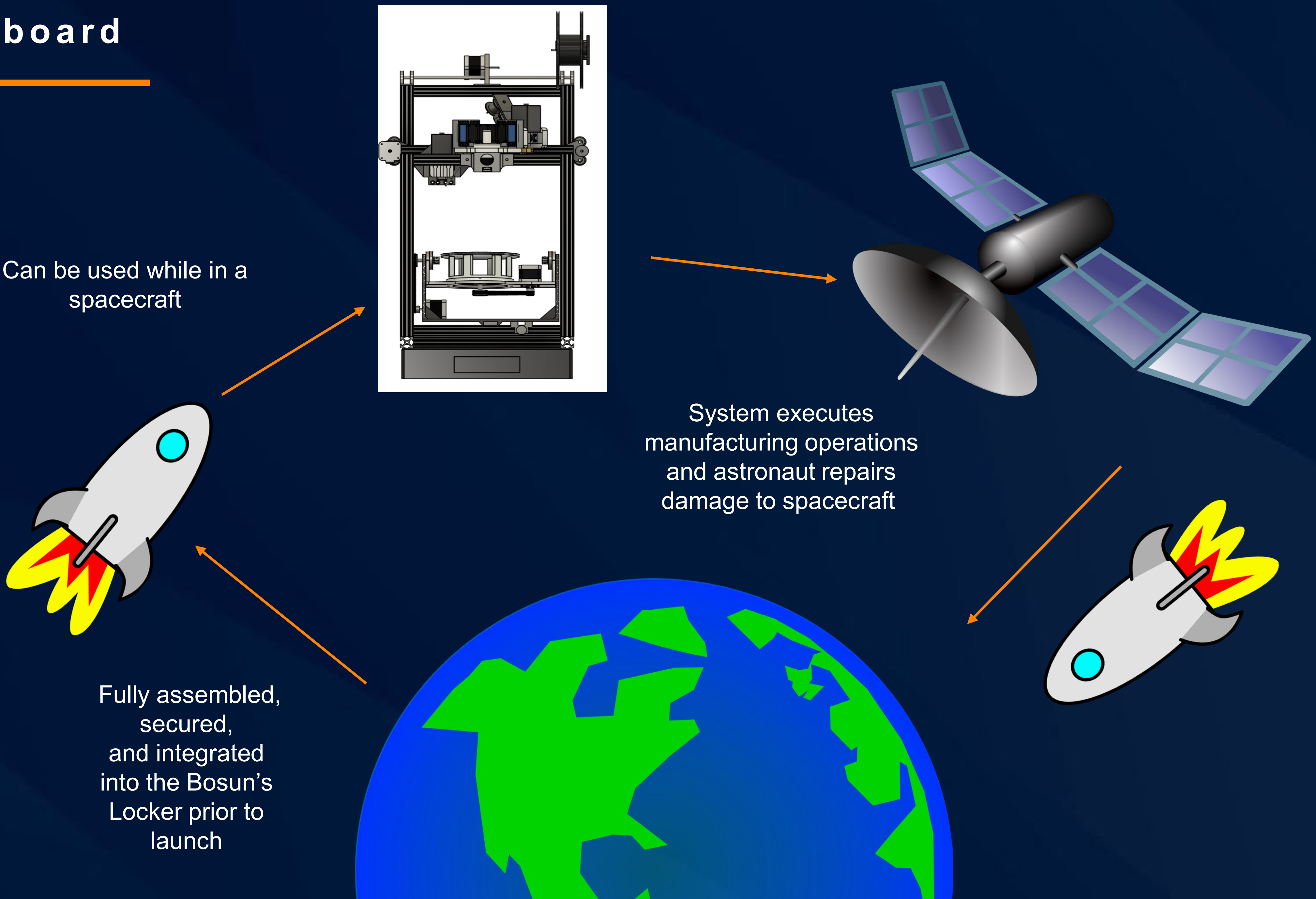
- Solder temperatures exceeding 200°C or misaligned laser beams can cause material degradation, equipment damage, and hazardous specular reflections
- These risks are mitigated by utilizing an engineering model to verify heating parameters and implementing tuned **IR camera feedback** for real-time temperature monitoring
- In microgravity, metallic flakes and outgassed residues remain suspended, posing a threat of electrical shorts and mechanical binding in the gantry system
- Protection strategies include designing **shielded feeder housings**, establishing strict maintenance intervals, and using space-rated dry lubricants to prevent contamination



Animation



Storyboard



Can be used while in a spacecraft

System executes manufacturing operations and astronaut repairs damage to spacecraft

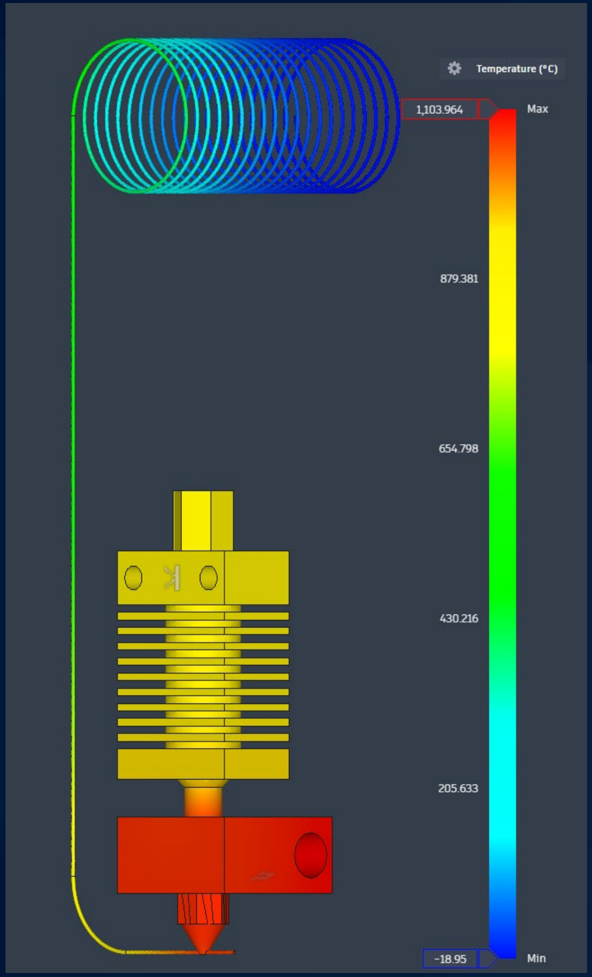
Fully assembled, secured, and integrated into the Bosun’s Locker prior to launch

Results

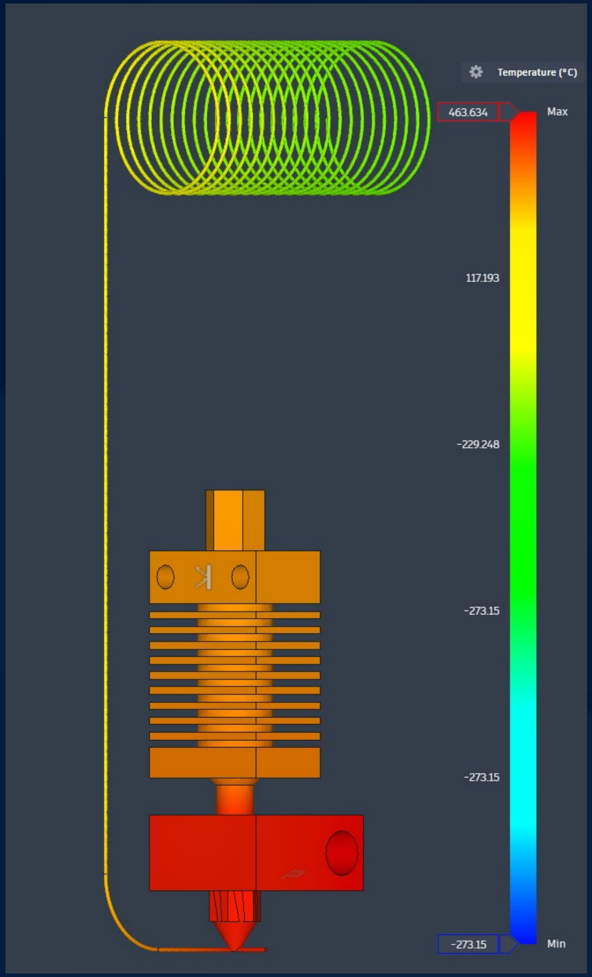
Thermal Simulation, Power Consumption, FEA

Thermal Simulations: Heated Printing Nozzle

- The thermal simulation was done to determine heat dissipation capability under max power
- The printing nozzle was assumed to operate with an applied load of 50W at the inner heat cartridge face
- The environment was assumed to be -270°C and convection-less to simulate low orbit conditions
- The low emissivity simulation had a max **temperature of 1103°C** and **high heat creep**
- The high emissivity simulation had a max **temperature of 463°C** and **lower heat creep**



Low Emissivity Simulation
ε = 0.05. e.g. Polished Metal



High Emissivity Simulation
ε = 0.8. e.g. Anodized Metal

Power Analysis

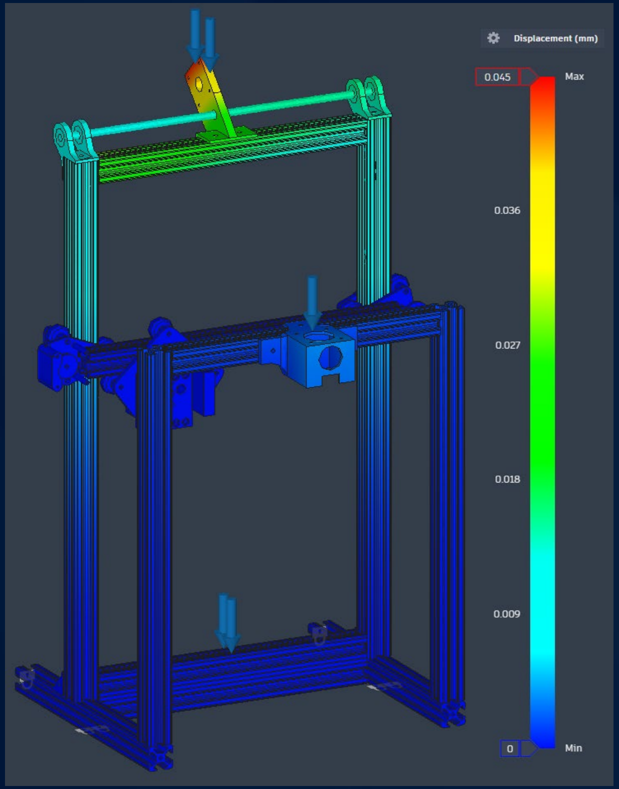
- To ensure the system operates within the maximum power limits of **1000 W peak** and **300 W continuous**, we calculated the total power consumption of the entire system
- The operating torque for the motors was also calculated to ensure the selected motors could sustain the load imposed by the system's weight
- The total maximum power calculated was **429.8 W**, with the general system power consumption at **150.8 W**

Component	Max Power (W)	General Operating Power (W)	Quantity	Total MAX	Total General
Stepper motor	9.6	2.4	8	76.8	19.2
Print Hot Bed	300	100	1	300	100
Nozzle heater	50	30	1	50	30
Servomotor	1.5	0.8	2	3	1.6

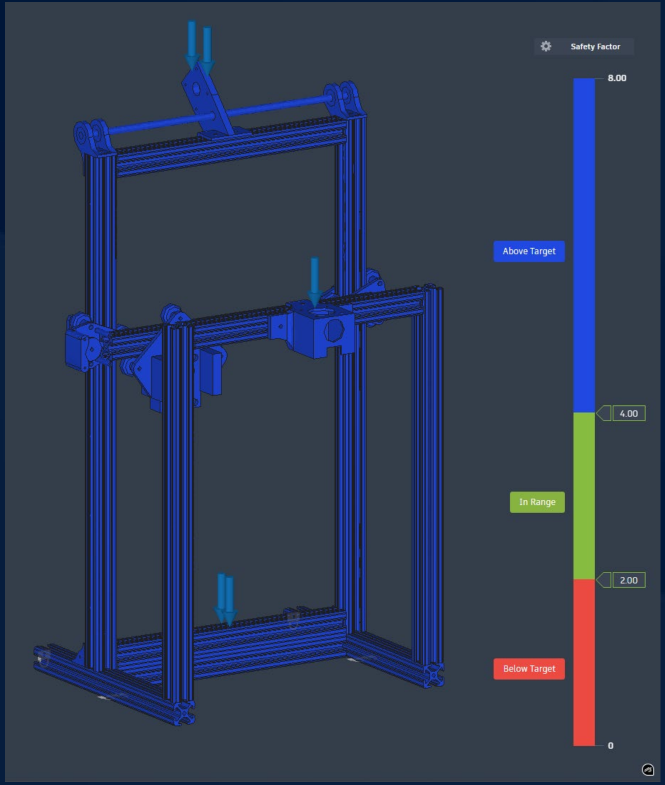
Total System Power (MAX)	Total System Power (General)
429.8 W	150.8 W

Structural Analysis - FEA

- The stress experienced by the gantry and the resulting displacement were minimal, showing its structural integrity under the applied load
- The simulations assume Earth conditions and represent the subsystems' weights as point loads
- Simulations resulted with a **safety factor of 15** and a **maximum displacement of 0.045mm**, confirming the gantry’s reliability under operating conditions



Max displacement simulation in Fusion360



Safety Factor simulation in Fusion360

Future Work

- **Prototype Fabrication**: Transition the conceptual designs for the toolheads and the rotary exchanger into a physical prototype to validate the mechanical tool-changing sequence
- **Thermal Testing**: Subject the prototype to 350°C operating conditions to ensure the gear-driven locker and gantry remain functional under high thermal loads
- **Precision Alignment**: Refine the tolerances between the multi-axis print bed and the conceptual toolheads to ensure repeatable accuracy during autonomous operation
- **Debris Containment**: Test the sealed locker prototype to verify it successfully contains metallic flakes and prevents interference with the belt-driven gantry

System Requirements

- **Physical Dimensions** Designed to fit the **30.5 x 30.5 x 30.5 cm** volume of the Arkisys Bosun’s Locker with integrated mounting interfaces
- **Mass Allocation** Total system mass is **8.78 kg**, significantly under the **15 kg** maximum payload limit
- **Power Budget** Peak power consumption is capped at **430W**, maintaining a **57% safety margin** below the 1000W locker limit
- **Environmental Compatibility** All structural components utilize **PEEK** and **ULTEM 9085** to meet NASA outgassing and thermal stability standards for vacuum operation
- **Command & Control** Operates via semi-autonomous G-code sequences with four primary remote commands: **Start, Pause, Resume, and Abort**

Trade Study

Frame Material: Aluminum 6061-T6 vs. Carbon Fiber

- **Decision:** Selected **Aluminum 6061-T6** for its high strength-to-weight ratio and proven thermal conductivity in space environments, ensuring structural rigidity during high-speed printing

Thermal Management: Active vs. Passive Cooling

- **Decision:** Implemented **Passive Cooling** with aluminum heat sinks and high-performance insulation. This avoids the mechanical complexity and power draw of pumps/fans while maintaining safety

Motion Control: Open-Loop vs. Closed-Loop Motors

- **Decision:** Selected **High-Torque Stepper Motors with TMC2209 Drivers.** This provides the necessary precision for wire embedding without the extreme cost and weight of heavy industrial encoders

Tool Changing: Robotic Arm vs. Linear Rail Exchanger

- **Decision:** Developed a **Linear Rail Rotary Exchanger.** This design minimizes moving parts and reduces the potential for mechanical jamming compared to a multi-jointed arm
- **Manufacturing Method: Subtractive vs. Additive**
- **Decision:** Focused on **Additive Manufacturing (FDM).** Additive processes minimize material waste and allow for the complex internal geometries needed for integrated wire embedding

Data & Control Systems

- **Dual-Controller Architecture** Utilizes an **MKS Monster8 V2** for primary motion control and 8-axis management, paired with a host processor running **Klipper firmware** for high-speed G-code processing and tool-offset calculations
- **Intelligent Sensor Fusion** Integrated feedback loops monitor thermal states (thermistors), mechanical positioning (endstops), and electrical current in real-time to ensure precision and prevent hardware collisions
- **Semi-Autonomous Command Logic** Designed to function with minimal ground-station intervention. The system executes complex multi-tool sequences autonomously based on four high-level remote commands: **Start, Pause, Resume, and Abort**
- **Redundant Power & Safety** Independent power rails for logic and motors protect the controller from electrical noise and voltage spikes, ensuring stable data processing during high-torque manufacturing operations
- **Communication Interface** Uses a standard **USB/Serial interface** for reliable data transfer with the host satellite, allowing for status telemetry and health monitoring during the fabrication cycle

Conclusion

Project Summary

- Successfully developed a multifunctional, semi-autonomous manufacturing payload designed for the Arkisys Bosun's Locker. The system bridges the gap between raw material and functional orbital components

Key Achievements

- Integrated **3D printing, soldering, and wire embedding** into a single, compact unit
- Achieved a **15% mass reduction** and maintained a **57% power safety margin**
- Validated structural and thermal integrity through rigorous **NASA-standard simulations**

THANK YOU

Members: *Manuel Ruiz De Esparza, Brian Gamboa, Jofiel Zapata, Estrella Martinez, Ingrid Nunez, Franciso Miranda, Mario Solis, Ruben Espinoza, Juan Luna, John Smith, Vanessa Preciado*

Collaborators: *Adrianna Villegas, Alexander Pustinger*

Advisor: *Dr. Angel Flores Abad*

References

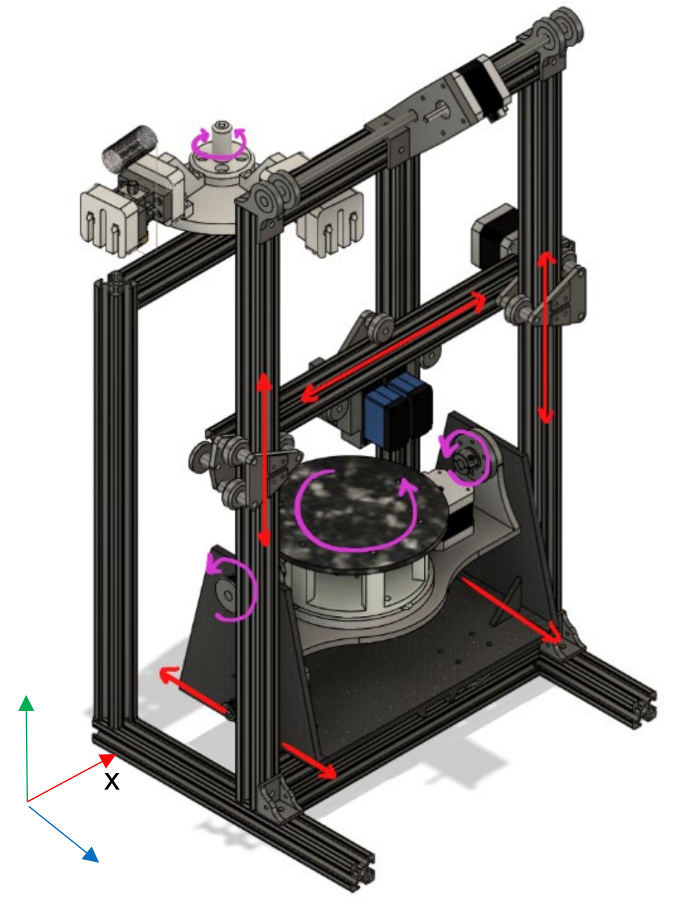
- Arkisys, Inc. *Arkisys | Modular Spacecraft*. Arkisys, Inc., 2025, https://www.arkisys.com/
- "Arkisys and iBoss Team up to Enable Orbital Bosun's Lockers for Students to Develop Payload Access for the Port." *EIN Press Wire*, 9 Aug. 2023, https://www.einpresswire.com/article/822743713/arkisys-and-iboss-team-up-to-enable-orbital-bosuns-lockers-for-students-to-develop-payload-access-for-the-port
- COSMIC (Consortium for Space Mobility and ISAM Capabilities).
  2025–26 COSMIC Capstone Challenge: Information Packet – Initial Release.
  Revision A, Document No. COSMIC-E01-WD005-2025-A,
  Released 17 July 2025, COSMIC, www.cosmicspace.org/c3
- National Aeronautics and Space Administration. "Additive Manufacturing of PEEK and Fiber-Reinforced PEEK for NASA Applications and Custom Medical Devices." *NASA TechPort*, Project No. 102286, techport.nasa.gov/projects/102286.
- Johnston, Mallory M., Mary J. Werkheiser, Kenneth G. Cooper, Michael P. Snyder, and Jennifer E. Edmunson. *3D Printing in Zero-G ISS Technology Demonstration.* NASA Marshall Space Flight Center, 4 Aug. 2014, doi:10.2514/6.2014-3881, ntrs.nasa.gov/api/citations/20140012888/downloads/20140012888.pdf.
- Prater, Tracie, Niki Werkheiser, Frank Ledbetter, and Alexander Jehle. *NASA's In-Space Manufacturing Project: Toward a Multimaterial Fabrication Laboratory for the International Space Station.* Conference Paper (AIAA Space Forum), 17 Sept. 2018, NASA Marshall Space Flight Center, Document No. 20180006362, https://ntrs.nasa.gov/api/citations/20180006362/downloads/20180006362.pdf
- European Space Agency. "ESA Launches First Metal 3D Printer to ISS." *ESA*, 31 Jan. 2024, https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/ESA_launches_first_metal_3D_printer_to_ISS.
- Saari, Matt, Bryan Cox, Edmond Richer, Paul S. Krueger, and Adam L. Cohen. "Fiber Encapsulation Additive Manufacturing: An Enabling Technology for 3D Printing of Electromechanical Devices and Robotic Components." *3D Printing and Additive Manufacturing*, vol. 2, no. 1, Mar. 2015, pp. 32-39, doi:10.1089/3dp.2015.0003.
- Instructables. (2020, September 23). *DIY Automatic Tool Changer for MPCNC*. Instructables. https://www.instructables.com/DIY-Automatic-Tool-Changer-for-MPCNC/

Backup slides

Operation Diagrams

- The red arrows describe the system's translational axes: the print bed moves along the y-axis and the toolhead moves along the x and z-axes.

- The purple arrows show which components will rotate during operation – the print bed with rotate about the x and z axes during prints and the toolhead exchanger rotates as needed.

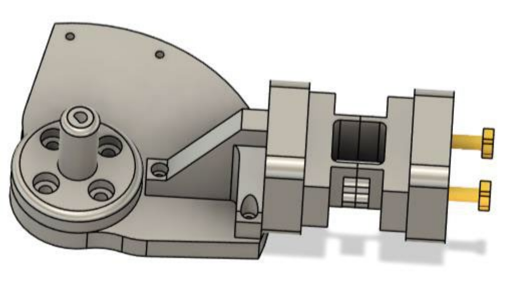


Manufacture

- The manufacturing team successfully printed the rotary tool, ensuring that the mechanical and mounting features were accurate.

- This allowed other team members to begin running preliminary tests, such as verifying rotation smoothness, checking alignment, and observing how the tool interacted with the rest of the system.

- These evaluations helped confirm that the printed part operated as intended and provided feedback for potential improvements.



Objectives

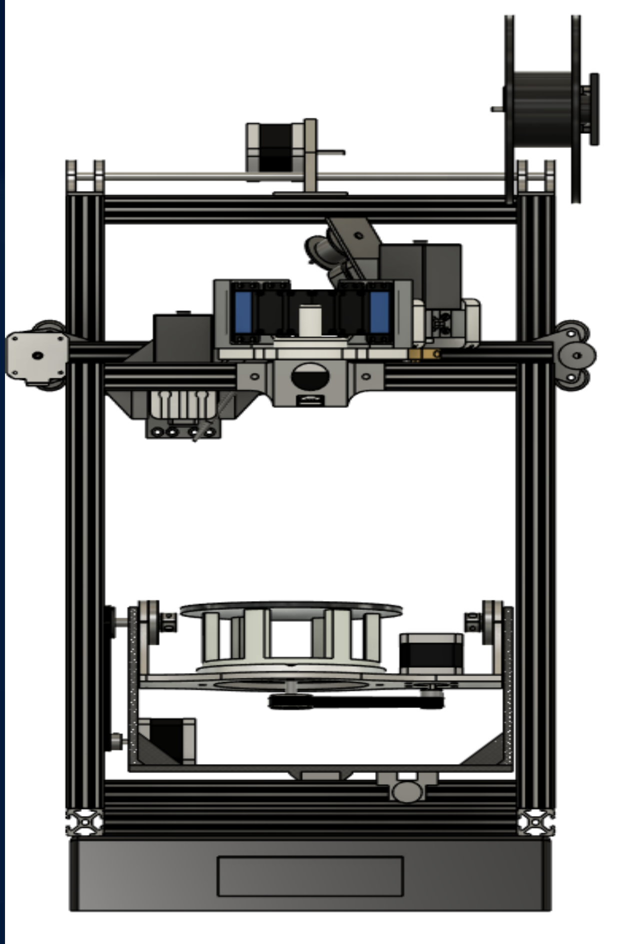
- Develop a compact and autonomous manufacturing system specifically designed for integration with the Arkisy's Bosun's Locker platform.

- Enable multi-functional fabrication capabilities, including 3D printing, soldering, and wire embedding.
- Design an automated tool-changing mechanism to facilitate uninterrupted and efficient operation.

- Ensure compatibility with spaceflight requirements by adhering to NASA-STD-6030 and relevant material standards.

- Integrate advanced sensors and control systems to support autonomous and safe operation.

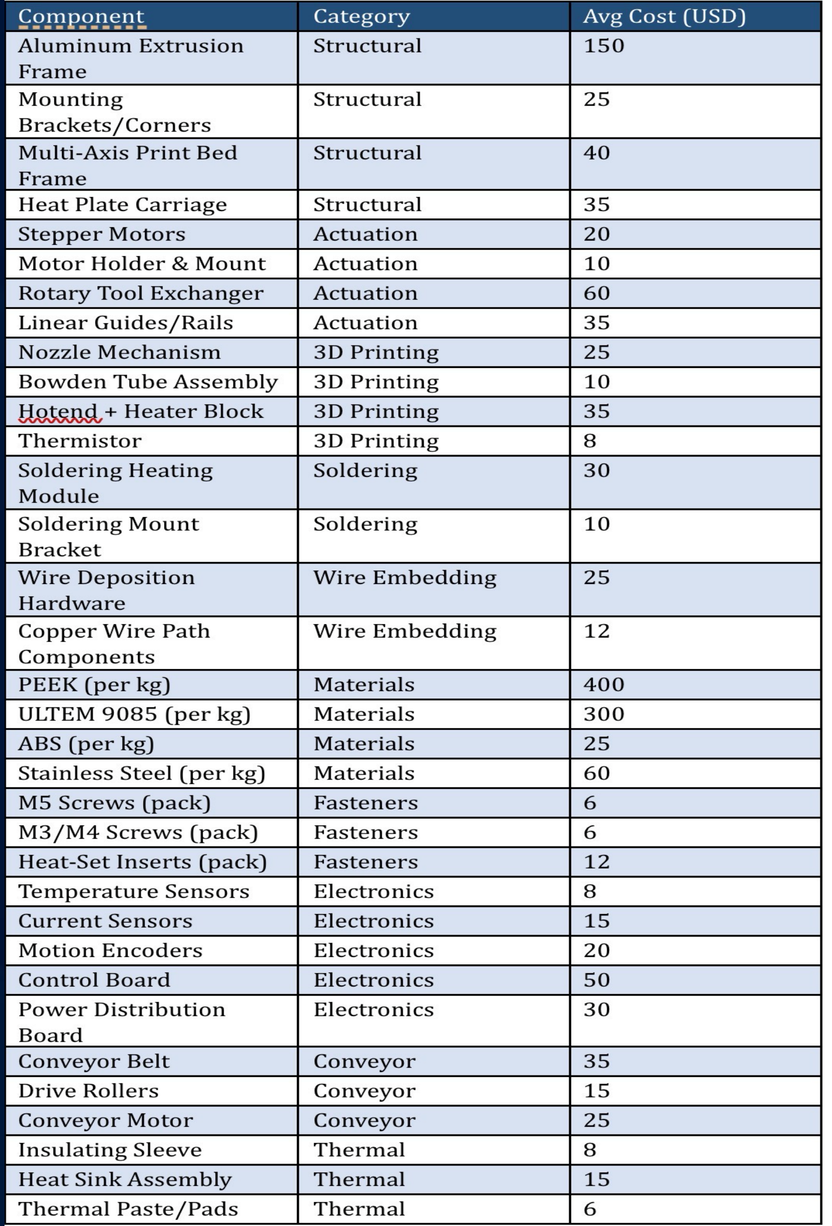
- Validate system performance using computer-aided design (CAD), thermal simulations, and prototype testing.



Goals

- Create a self-contained fabrication payload optimized for the constraints and interfaces of the Bosun's Locker environment.
- Provide a unified manufacturing platform capable of performing multiple fabrication processes to support on-orbit construction and repair.
- Select materials, components, and fabrication methods that satisfy aerospace-grade safety, outgassing, and durability requirements for orbital use.
- Employ sensing, monitoring, and control architecture that enables the payload to regulate temperature, motion, and electrical behavior independently.
- Demonstrate functionality and compliance trough iterative modeling, subsystem evaluation, and experimental verification.
- Provide a versatile manufacturing capability that supports additive production, electronic joining, and conductive pathway creation in a single compact system.

BILL OF MATERIALS



Component	Category	Avg Cost (USD)
Aluminum Extrusion Frame	Structural	150
Mounting Brackets/Corners	Structural	25
Multi-Axis Print Bed Frame	Structural	40
Heat Plate Carriage	Structural	35
Stepper Motors	Actuation	20
Motor Holder & Mount	Actuation	10
Rotary Tool Exchanger	Actuation	60
Linear Guides/Rails	Actuation	35
Nozzle Mechanism	3D Printing	25
Bowden Tube Assembly	3D Printing	10
Hotend + Heater Block	3D Printing	35
Thermistor	3D Printing	8
Soldering Heating Module	Soldering	30
Soldering Mount Bracket	Soldering	10
Wire Deposition Hardware	Wire Embedding	25
Copper Wire Path Components	Wire Embedding	12
PEEK (per kg)	Materials	400
ULTEM 9085 (per kg)	Materials	300
ABS (per kg)	Materials	25
Stainless Steel (per kg)	Materials	60
M5 Screws (pack)	Fasteners	6
M3/M4 Screws (pack)	Fasteners	6
Heat-Set Inserts (pack)	Fasteners	12
Temperature Sensors	Electronics	8
Current Sensors	Electronics	15
Motion Encoders	Electronics	20
Control Board	Electronics	50
Power Distribution Board	Electronics	30
Conveyor Belt	Conveyor	35
Drive Rollers	Conveyor	15
Conveyor Motor	Conveyor	25
Insulating Sleeve	Thermal	8
Heat Sink Assembly	Thermal	15
Thermal Paste/Pads	Thermal	6

Solder Temperature Too High

Statement ID: 1	**Solder Temperature reaches above 200°C**
Context	Above this temperature the mechanical properties can degrade if exposure time above 200°C is prolonged. While standard soldering often targets 350°C to ensure wetting, in a continuous laser-driven path triggers rapid embrittlement and vaporization. In microgravity, this vaporization creates hazardous floating particles that pose electrical risks.
Mitigation	Utilize terrestrial lab setup (Terrestrial Twin) to verify heating parameters. Further, tune the IR camera temperature output for a rough solder temperature estimation, utilize the tuned reading to identify overheating and end exposure
Overall Status:	Consequence: 2 Likelihood: 3 Mission Essential: Yes

Laser Module Overheats

Statement ID: 2	**If the laser module that is outputting the optical light overheats, the electronics will break**
Context	The module is a necessary part of the experiment; most modules have temperature monitoring to stop emitting once it reaches a certain temperature. However, the main concern is that it stops in the middle of soldering.
Mitigation	Implement a maximum initial temperature on the module that must be described on the coupon QR code (since it also describes how much power it must use as well), this must be verified on the Terrestrial Twin
Overall Status:	Consequence: 2 Likelihood: 3 Mission Essential: Yes

Laser Scattering

Statement ID: 3	**The laser scatter light bypasses the enclosure, causing safety concerns**
Context	The current design utilizes an enclosure system to prevent high amounts of optical power from escaping. However, if the enclosure is damaged or a gap occurs, this becomes a major hazard. Solder wire and metallic substrates are highly reflective; the cylindrical geometry of the wire acts as a specular reflector that can redirect laser energy in a 360-degree arc. This stray energy can degrade non-metallic components like POM wheels and timing belts or interfere with IR camera thermal sensors.
Mitigation	Maintain a robust enclosure to prevent light from escaping the work volume. Utilize the Terrestrial Twin to test alignment and minimize reflections toward sensitive gantry components
Overall Status: Consequence: 5 Likelihood: 1 Mission Essential: Yes	

Laser Burning

Statement ID: 4	**Due to the reflectiveness of the solder, the laser light will scatter, and it's direction could be towards the substrate (<1-2mm away from solder).**
Context	Substrates susceptible to the laser wavelength could exhibit burning which can skew IR information. We don't know if burning degrades the solder. This can be avoided by careful selection of substrate material that does not absorb laser light.
Mitigation	**Substrate Selection**: Use materials specifically chosen for their low absorption of the laser's wavelength to prevent localized burning. **Alignment Verification**: Perform thorough testing of the laser alignment and wire feed positioning through the Terrestrial Twin to minimize off-target energy. **Thermal Feedback Monitoring**: Use the tuned IR camera to detect unexpected heat signatures on the substrate that indicate scattering.
Overall Status:	Consequence: 4 Likelihood: 4 Mission Essential: No

Wire Stripping and Grip Loss

Statement ID: 5	**Metallic flakes generated at the gear teeth may settle on the timing belts or POM wheels.**
Context	Solder is a soft, malleable alloy. The gear teeth must bite into the wire to ensure positive displacement. In a microgravity environment, the resulting metallic debris will not settle and can migrate into the Belted Gantry System. This poses a risk of electrical shorts in the Rotary Tool Exchanger or mechanical binding in the timing belt bearings and POM wheels.
Mitigation	**Debris Containment**: Design the feeder housing to be shielded or enclosed to trap metallic flakes at the point of generation. **Terrestrial Twin Testing**: Use the lab setup to quantify the amount of debris generated over extended feeding cycles and inspect for migration patterns. **Maintenance Intervals**: Establish a schedule for inspecting and cleaning the gantry components to prevent cumulative buildup of conductive particles.
Overall Status:	Consequence: 4 Likelihood: 3 Mission Essential: Yes

Optical Kickback

Statement ID: 6	**The cylindrical geometry of the solder wire acts as a specular reflector, potentially redirecting laser energy toward sensitive gantry components.**
Context	Solder wire is highly reflective. A misaligned wire feed can reflect the laser beam in a 360-degree arc perpendicular to the wire. This stray energy could hit and degrade non-metallic components, such as the POM wheels or timing belts, or interfere with the IR camera’s thermal sensors.
Mitigation	**Beam Alignment:** Perform rigorous alignment checks using the Terrestrial Twin to ensure the laser's angle of incidence minimizes back-reflection into the gantry. **Sensor Shielding**: Equip the IR camera with optical filters to prevent sensor saturation from reflected laser light. **Material Selection**: Use laser-resistant materials for critical gantry components that may be in the path of potential specular reflections
Overall Status: Consequence: 4 Likelihood: 2 Mission Essential: Yes	

Thermal Creep in Feed Mechanism

Statement ID: 7	**Conductive heat transfer up the solder wire may soften the material within the drive gears, causing a feed failure.**
Context	Solder wire has high thermal conductivity. During prolonged soldering operations, heat from the melt pool can travel up the wire. If the wire reaches its softening point while still inside the gear drive, the teeth will lose the ability to push the wire, resulting in a jam or "bird-nesting" at the feeder entrance.
Mitigation	**Feed Rate Optimization**: Use the Terrestrial Twin to establish feed rates that ensure the wire moves faster than the thermal conduction rate, keeping the "soft" section of the wire outside the drive gears. **Active Cooling**: Implement heat sinking or localized cooling on the feeder housing to dissipate conducted heat before it reaches the gears. **Thermal Modeling**: Validate the heat-affected zone (HAZ) of the wire during continuous operation to set maximum "on-time" limits for the laser.
Overall Status:	Consequence: 3 Likelihood: 3 Mission Essential: Yes

Internal Gantry Contamination (Debris)

Statement ID: 8	**Foreign Object Debris (FOD) or material buildup within the belted gantry system causes mechanical interference or electrical failure.**
Context	The experiment operates within a belted gantry system where timing belts, bearings, and POM wheels are exposed to the internal environment. While Risk ID 5 focuses specifically on metallic flakes from the feeder, this risk encompasses general debris, including outgassed residues from the soldering process or loose hardware. In microgravity, this debris does not settle at the bottom of the enclosure and instead remains suspended, increasing the likelihood of it becoming trapped in the rotary tool exchanger or between the timing belt and pulleys. This can lead to skipped steps in the gantry movement, premature wear of the POM wheels, or intermittent electrical shorts.
Mitigation	**Pre-Flight Cleaning**: Ensure the gantry and all belted components are ultrasonically cleaned and free of lubricants that might attract and hold suspended debris. **Gantry Shielding**: Implement physical brush-seals or deflectors around the timing belts and pulleys to prevent suspended particles from entering the drive "pinch points.“ **Terrestrial Twin Stress Test**: Run the gantry in a debris-heavy environment (simulated with solder flakes) in the lab to identify which specific bearings or sensors are most vulnerable to contamination.
Overall Status:	Consequence: 4 Likelihood: 4 Mission Essential: No

Solder Does Not Stick (Wetting Failure)

Statement ID: 9	**The solder wire fails to adhere to the substrate or the previous layer, leading to a structural or electrical failure.**
Context	In a wire-fed laser system, successful "wetting" depends on the precise thermal balance between the laser power, the wire feed rate, and the substrate temperature. If the substrate is too cold or the laser power is insufficient, the solder will "ball up" due to surface tension rather than spreading and bonding. In microgravity, this is exacerbated because buoyancy-driven convection is absent, meaning heat does not dissipate as it does on Earth, potentially leading to inconsistent bonding zones. Furthermore, if the substrate is contaminated or has an oxide layer that the laser cannot break through, the solder will fail to stick, resulting in "floating" or unanchored segments.
Mitigation	**QR Code Power Profiling:** Ensure the QR code on the coupon specifies the correct laser power and pre-heat duration required for the specific substrate material to promote wetting. **IR Camera Feedback:** Use the tuned IR camera to verify that the substrate has reached the minimum wetting temperature before the wire feed begins. **Terrestrial Twin Surface Prep:** Use the lab setup to test different substrate cleaning and preparation methods to ensure a reliable bond under vacuum or microgravity-simulated conditions.
Overall Status:	Consequence: 4 Likelihood: 4 Mission Essential: No

Mechanical Binding of Sealed Locker

Statement ID: 10	**The sealed locker door or internal mechanical components bind due to thermal expansion or debris interference.**
Context	To contain the laser and any potential metallic flakes, the experiment is housed in a sealed locker. However, the heat generated by the laser 350C to 400C) and the diode itself can cause thermal expansion of the internal gantry rails or the locker's locking mechanism. If the internal temperature rises significantly during long 3D printing or soldering runs, the POM wheels or timing belts may expand at different rates than the aluminum frame, causing the gantry to "skip" steps or the locker to become stuck in a closed position.
Mitigation	**Thermal Expansion Clearances:** Design the gantry and locker interfaces with sufficient tolerances to account for material expansion at maximum operating temperatures. **Internal Temperature Monitoring:** Use the laser module's internal sensors and the IR camera to monitor the "ambient" temperature inside the sealed locker. **Lubrication Selection:** Use dry, space-rated lubricants that do not outgas or become "tacky" when exposed to the heat of the laser.

Overall Status: Consequence: 4 Likelihood: 2 Mission Essential: No