

COSMIC Challenge Orbital Textile Manufacturing via Autonomous Rapier-Based Weaving System

Team Buckeyes | The Ohio State University



Tyler Smith

Dual Degree:
Mechanical/Electrical
Engineering



Hayden Morrison

Electrical/Computer
Engineering
Mechanical Background



Matt Fisher

Engineering Physics
Aerospace Conc.
Minor: Technical Theatre



Bence Dobo

Mechanical Engineering



Isaac Appiah-Boateng

Information Security
Minors: Computer Science
and Engineering Sciences



Varsha Venkateshwaran

Electrical/Computer
Engineering

Abstract

As space missions extend in duration and distance from Earth, reliance on pre-manufactured materials becomes increasingly unsustainable. Textiles are critical for applications including spacesuit repair, habitat insulation, and flexible structural reinforcement, yet they are currently manufactured exclusively on Earth and launched as cargo. This creates limitations in adaptability, cost, and mission resilience.

This work presents the design and prototyping of an autonomous, microgravity-compatible textile manufacturing system capable of producing woven materials within the constraints of Arkisys' Bosun's Locker. The system utilizes a rapier-based weaving architecture optimized for low power consumption, compact packaging, and reliable operation in microgravity conditions.

A functional prototype was developed to demonstrate the feasibility of in-space textile manufacturing. The prototype successfully integrates mechanical, electrical, and software subsystems to execute a chain of operations including yarn tensioning, controlled weft insertion, thread capture, and beat-up motion. Validation testing focuses on autonomy, reliability, and gravity independence.

Through trade studies, system-level design, and prototype validation, this work demonstrates that autonomous in-orbit textile manufacturing is feasible within realistic constraints. The resulting system provides a scalable pathway toward sustainable material production for long-duration space missions and contributes directly to advancing In-Space Servicing, Assembly, and Manufacturing (ISAM) capabilities.

1 Introduction

1.1 Background and Overview

Future space missions, including lunar habitation and Mars exploration, require increased autonomy and reduced dependence on Earth-based resupply systems. Currently, textiles used in space applications are entirely manufactured on Earth and launched as cargo, leading to significant limitations:

- High launch cost due to volume and mass
- Lack of adaptability to unforeseen mission needs
- Inability to perform real-time repairs

Textiles play a crucial role in space systems, including:

- Spacesuit layers and repair patches
- Habitat insulation materials
- Flexible structural components

The absence of in-space textile manufacturing presents a critical gap in In-Space Servicing, Assembly, and Manufacturing (ISAM) capabilities.

1.2 Project Objective

The objective of this project is to design and validate a compact, autonomous system capable of demonstrating that producing woven textile materials is feasible in a microgravity environment. To meet the constraints and design goals of this objective, the system must do the following:

- Fit within the Bosun's locker enclosure
- Operate under strict power constraints
- Execute a chain of at least three discrete manufacturing operations
- Function semi-autonomously with minimal human intervention

In order to meet these objectives, the team developed a rapier based weaving system designed for microgravity compatibility and validated its feasibility through physical prototyping.

1.3 Approach and Scope

In order to manage the approach and scope of this project, our team decided to follow a systems engineering approach. We began with defining the problem, understanding the requirements from our stakeholders, identifying our own internal design goals and defining the challenges involved with working in microgravity. Then, we moved to generating concepts that would meet these design goals and completed trade studies to assess which concept would meet these goals the best. After a concept was selected, the team developed a prototype in accordance with the project scope and concept map generation. The prototype was then validated and evaluated against the mission requirements informed via prior stakeholder analysis.

2 Problem Definition and Requirements

2.1 Problem Statement

Space missions currently depend entirely on Earth-manufactured textiles. This dependency limits astronaut safety, mission adaptability, and long-term sustainability. No compact, microgravity-compatible textile production system exists that can autonomously produce woven fabrics within the spatial and power constraints of a hosted payload enclosure such as the Bosun's Locker.

The COSMIC Capstone Challenge addresses this gap directly by tasking student teams with designing a payload that demonstrates a chain of three or more discrete operations providing an important capability for orbital manufacturing. Team Buckeyes at The Ohio State University has chosen orbital textile weaving as its mission.

2.2 Stakeholder Analysis

Four primary stakeholder groups shape the requirements of this project:

- Astronauts and mission crew: Direct users of textiles produced in orbit. Primary concerns are safety, on-demand availability of repair materials, and ease of interaction with an autonomous system during emergencies.
- NASA and international space agencies (ESA, JAXA, ISRO): Require compliance with NASA safety and quality standards, ASTM textile specifications, and ASME hardware standards. Interested in long-term cost reduction and mission extensibility.
- COSMIC and the space industry: Seeks demonstration of ISAM capabilities that can be matured into funded missions, advancing the national ISAM strategy.
- Future space mission architects: Long-duration mission planners who would benefit from scalable, autonomous manufacturing infrastructure on the Moon or Mars, where Earth resupply is impractical or impossible.

2.3 Design Requirements

The following design requirements were derived from the team's House of Quality analysis, the COSMIC Track 1 challenge specification, and Arkisys' Bosun's Locker Interface Control Drawing.

Table 1: Design Requirements

Requirement	Target Value
Payload volume	Fit within 15.75 in x 15.75 in x 35.45 in
Payload mass	400 kg maximum
Sustained power	300 W maximum
Number of operations	3 or more discrete operations
Autonomy level	Semi-autonomous, limited remote commands
Output product	150 mm x 75 mm woven patch
EMI shielding	10^7 V/m minimum
Operating temperature	Below 75 degrees C
Prototype budget	3500 USD maximum
Operational duty cycle	30 percent

2.4 Key Challenges in Microgravity Weaving

Conventional textile manufacturing has gravity acting in ways that are easy to overlook on Earth. Gravity keeps yarn tensioned on the beam, holds fibers against guide surfaces, maintains warp alignment under the loom's own weight, and ensures weft threads settle into position after insertion. In microgravity, all these acts differently. Thread floats freely, mechanisms that rely on gravitational friction become unreliable, and loose fibers can escape into the cabin environment, posing contamination and inhalation of hazards.

The team identified four primary technical challenges that drove the entire design direction: (1) maintaining reliable yarn tension without gravitational assistance throughout the pick cycle; (2) constraining rapier mechanism travel to prevent lateral drift during insertion and retraction; (3) containing loose fibers within the Bosun's Locker enclosure to prevent cabin contamination; and (4) ensuring all moving parts function equivalently regardless of orientation relative to gravity. Each of these challenges is addressed in the subsystem designs described in Section 4.

2.5 Material for Future Work: Beta Cloth

Beta cloth (PTFE-coated woven fiberglass) was selected as the primary yarn and production material for the Space Loom prototype and target orbital system. Beta cloth has decades of flight heritage in NASA spacesuits and spacecraft insulation. It is highly resistant to fire, abrasion, radiation, and extreme temperatures, and its woven fiberglass base is compatible with rapier insertion mechanisms. The PTFE coating provides chemical stability in the orbital environment and reduces fiber shedding during handling.

For shorter orbital missions, thermal cycling stress on Beta cloth is manageable. For very long-duration missions, the team acknowledges that alternative high-performance textile materials may be required, including ceramic fiber composites or metal mesh weaves. This is identified as an open item for future material trade studies beyond the scope of the current prototype.

3 Concept Generation and Trade Studies

3.1 Textile Manufacturing Method Selection

The team evaluated five candidate production methods against five weighted criteria: microgravity compatibility, compactness within the Bosun's Locker, level of achievable autonomy, material versatility, and maturity of available technology. The comparison is summarized in Table 2.

Table 2: Textile Manufacturing Methods Trade Study

Method	Pros	Cons	Microgravity Rating
Earth-made resupply	High quality, proven	High cost, no adaptability	Not applicable

Weaving (rapier)	Scalable, diverse yarns, well-understood	Requires tension adaptation	High
3D printing (FDM)	Any pattern, additive	High heat, limited to polymers	Moderate
Non-woven thermal bonding	Fast, cost-effective	Hazardous chemicals, high heat in enclosure	Low
Knitting	Comfortable, flexible fabrics	Snags and unravels easily	Moderate

Rapier-based weaving was selected as the most viable approach. Its advantages over the alternatives are decisive for this application: it operates continuously without generating significant heat, it accepts a wide variety of yarn types including Beta cloth fibers with proven spaceflight heritage, it produces structurally robust interlocked weaves suitable for load-bearing repair applications, and its mechanism is inherently compact and constrainable within a rigid frame. Knitting was rejected for structural reasons (woven fabrics resist tearing and unraveling better than knits). Non-woven bonding was rejected for safety reasons (chemical agents or open heat sources in a pressurized enclosed payload are incompatible with crewed platform operations). 3D printing was rejected for power, heat, and material flexibility reasons.

3.2 Weft Insertion Method Trade Study

Within rapier-based weaving, the team evaluated four sub-variants: single rapier, double rapier, telescoping rapier, and electromagnetic (non-contact) weft insertion. The electromagnetic concept was proposed as a potentially elegant contactless solution for microgravity, offering the appeal of no moving parts in contact with the yarn during insertion. However, quantitative power analysis eliminated it as a candidate before CDR.

The electromagnetic system was estimated to require six electromagnets, each drawing approximately 40 W, plus 60 W for control, sensors, and one shedding motor, totaling approximately 340 W of sustained power draw. This directly exceeds the Bosun's Locker's 300 W sustained limit and represents one of the most instructive lessons from the project: attractive conceptual solutions must be subjected to first-principles quantitative analysis early, before significant design investment is made.

Table 3: Rapier Trade Study

Feature	Double Rapier	Single Rapier (Selected)	Electromagnetic
---------	---------------	--------------------------	-----------------

Reliability	Proven, consistent	Proven, mechanically simpler	Complex, less flight-tested
Power draw	Low and predictable	Low and predictable	340 W estimated (exceeds limit)
Precision	High positional accuracy	High with encoder feedback	Limited by field variation
EMI risk	Low	Low	High, possible platform interference
Mechanical complexity	Moderate (two rapiers)	Lower (one rapier plus grabber)	High (thermal and electrical)
Scalability	Good	Good	Poor, power and control scale badly

The double rapier was the team's first preference because two rapiers meeting at the center of the shed cuts individual travel distance in half, enabling faster picks. At PDR, the double rapier was selected as the primary concept. During CDR-phase design iteration, the team refined this to a single rapier with a mechanical grabber handoff at the far end of the shed. This adjustment was driven by two practical findings: first, a single rapier simplifies synchronization and reduces part count and motor count without meaningfully sacrificing speed at the target patch dimensions (150 mm x 75 mm); second, a positive mechanical grabber provides more reliable thread transfer in microgravity than relying on passive tension to guide a second rapier's nosepiece to intercept the thread at the center of the shed. Table 3 reflects both the original double rapier evaluation and the final single rapier selection.

The beat-up mechanism uses a belt-driven linear actuator rather than a traditional pivoting beater bar. This provides direct positional control of the beater stroke, is compatible with operation in any orientation, and avoids the rotational inertia of a swinging beater that could generate undesirable attitude disturbances on a hosted payload platform.

3.3 Final Design Selection

After completing numerous trade studies, the team was able to make final decisions related to the type of mechanism, the major moving components, how we planned to establish a frame, and our plans for any custom components.

Concerning the main subject of the trade studies, the weft insertion method proved to be the most difficult decision for us to make due to the requirement for extensive research in an unfamiliar area. After this was completed, the team decided the final system will use a single rapier with

mechanical grabber handoff. This design reduces the number of moving components, eliminates potential synchronization issues with two rapiers, and provides a pathway for reliable thread control in microgravity. Overall, the single rapier represents the best balance between performance, complexity, and feasibility.

As for the major moving components, our team decided to use commercial off-the-shelf (COTS) products to facilitate a simple design with lots of industry usage and experience. For these COTS products, the team decided to look at Automation Direct for linear guides, motor mounting and couplers. Steppers Online will be the main vendor for stepper motors, servo motors, and stepper motor drivers.

For the framing and mounting, the team decided to use T-Slotted framing and accessories due to its ease of use and flexibility. If the project needed to be changed slightly, T-Slotted framing would allow for the flexibility to move components while still mounting them securely. In addition to T-Slotted framing, our team also planned to use custom 3D printed components for the grabber mechanisms, rapier, thread feed, and thread tensioning system.

4 System Design

4.1 Structural Packing and Bosun's Locker Integration

The Space Loom system is designed to operate within the dimensional constraints of Arkisys' Bosun's Locker, seen in Figure 1 below, which provides a fixed payload volume of approximately 15.75 in x 15.75 in x 35.45 in. This constraint drives the overall system architecture, requiring compact packaging and efficient spatial organization of all subsystems.

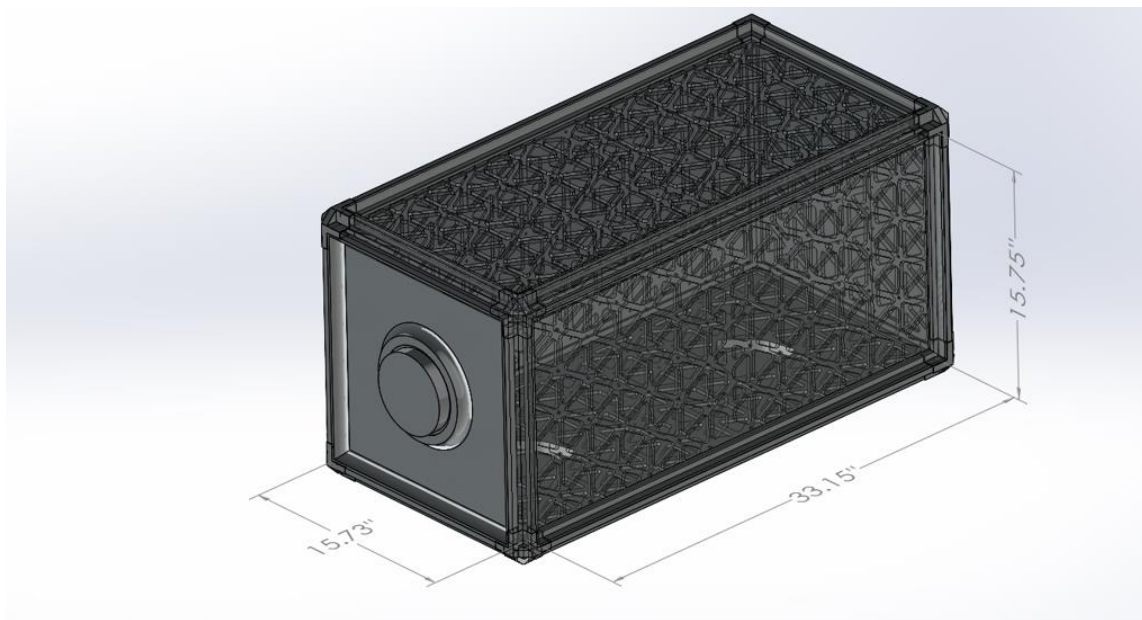


Figure 1: Bosun's Locker CAD Model

To allow for maximization of the space, the system frame is constructed using modular aluminum extrusion allowing high stiffness-to-weight ratio, adjustable mounting locations, and ease of assembly and iteration. An image of the CAD assembly inside the Bosun's locker can be seen below in Figure 2.

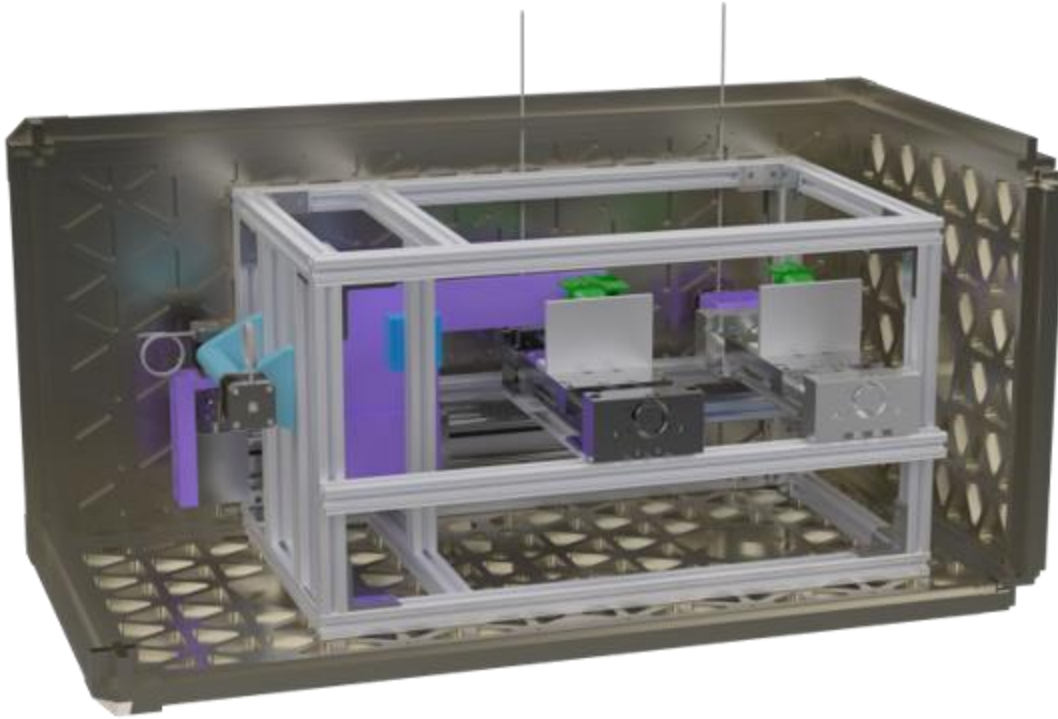


Figure 2: Space Loom Inside Bosun's Locker CAD Model

As can be seen in the image above, the packaging strategy for this system is organized into three layers. The bottom layer will consist of a base plate with all of our electronics. Power supplies, motor drivers, microcontrollers, wires and power distribution will all be housed here. The middle layer will consist of the mechanical actuation systems. The stepper motors and their respective linear guide systems will be contained here. The top layer will be where the weaving mechanisms will operate. The rapier mechanism is shown in purple, the yarn path is in blue, and the grabbers are green in the image above at the top of the system. This separation was used to minimize the interference between electrical and mechanical systems while maintaining accessibility.

This complete system fits within the Bosun's locker constraints while maintaining structural rigidity, accessibility for maintenance, and isolation of moving components.

4.2 Concept of Operations

The Space Loom system will operate as a semi-autonomous payload designed to execute a sequence of coordinated textile manufacturing operations. These operations will demonstrate multiple discrete operations of a larger manufacturing capability. To provide a full textile manufacturing capability, additional design, engineering, funds, and time would be required.

The operational sequence of this prototype listed as discrete operations is given below:

1. Yarn Feeding and Tensioning
 - a. Yarn is supplied from a spool and routed into the rapier mechanism. Future goals would be to have active control the maintains consistent tension independent of gravity
2. Weft Insertion (Rapier Motion)
 - a. The rapier transports the weft thread across the system along a linear guide
3. Thread capture (Grabber System)
 - a. A mechanical grabber captures and holds the thread at the far end
4. Beat-Up Operation
 - a. A linear actuator presses the inserted thread into the fabric structure
5. Cycle Reset
 - a. The system resets and prepares for the next cycle

These operations collectively demonstrate a potential solution to a portion of a semi-autonomous in-space textile manufacturing system.

4.3 System Architecture and Functional Level Decomposition

The Space Loom system is divided in three major functional groups: thread setup and control, weaving mechanism, and the control/electronics. The thread setup and control/electronics are necessary in any instance of prototype development. Thread setup will consist of a yarn spool system and tension control system. The control and electronics would consist of a microcontroller, sensor inputs, and a varying number of motor drivers and motors depending on the current implementation.

The weaving mechanism is more broadly defined as the discrete operations used to create textiles. To help identify the various parts of the textile manufacturing system, a system tree was created and is shown below in Figure 3.

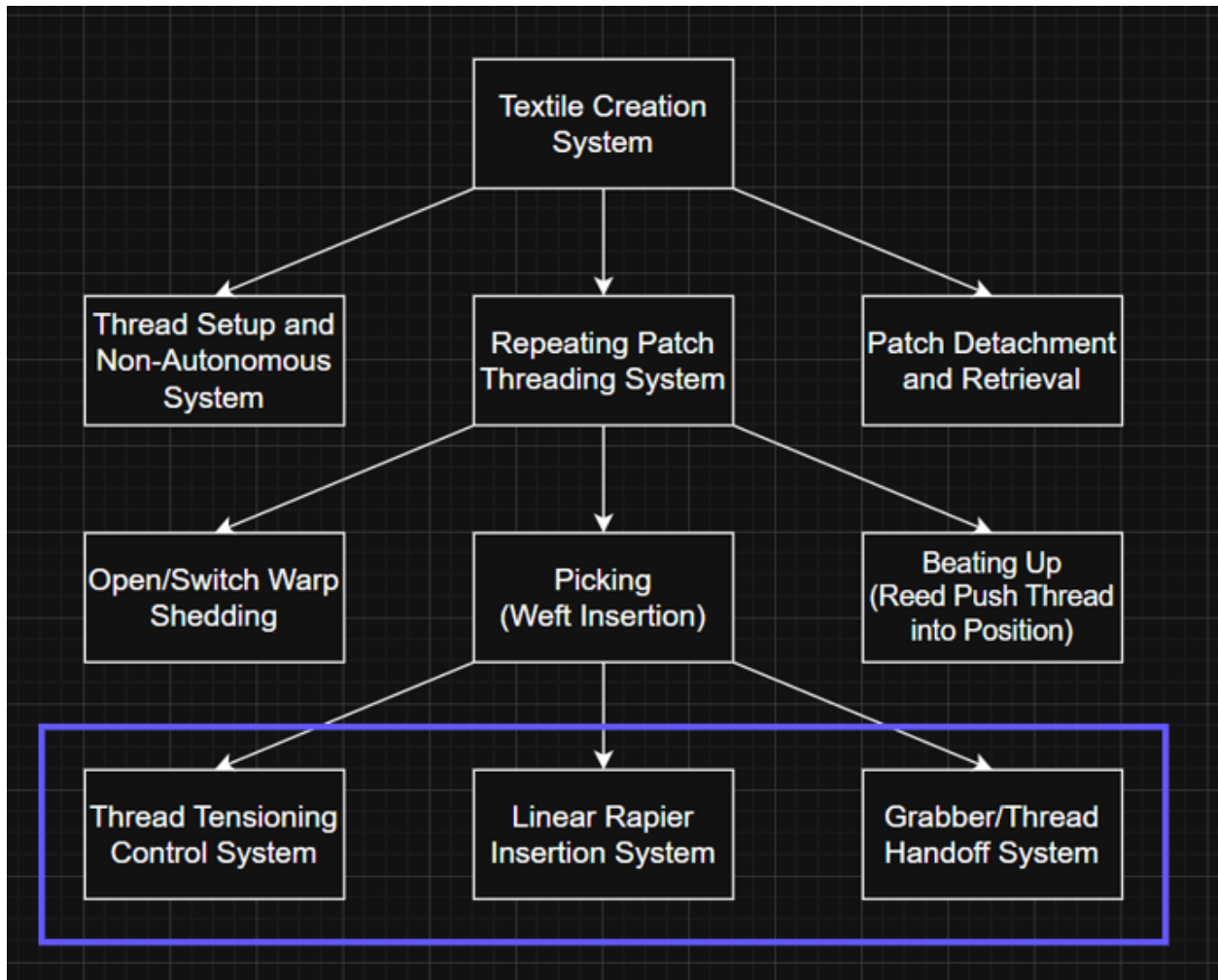


Figure 3: Space Loom Textile Manufacturing System Tree

In order to meet the time and budget constraints of this capstone project, our team elected to focus on the highlighted portion of the system. This system represents the minimum viable ISAM capability consisting of tensioning, insertion, capture, and consolidation. While this loop alone will not provide a stand-alone manufacturing capability, it does satisfy COSMIC's requirement of demonstrating a chain of manufacturing events and will provide guidance for feature iterations of the Space Loom system.

4.4 Prototype Development and Results

A fully integrated prototype was developed to validate the system described in the previous section. The purpose of this prototype was to assess system feasibility across mechanical, electrical, and software subsystems. An image of the fully assembled prototype can be found below in Figure 4.

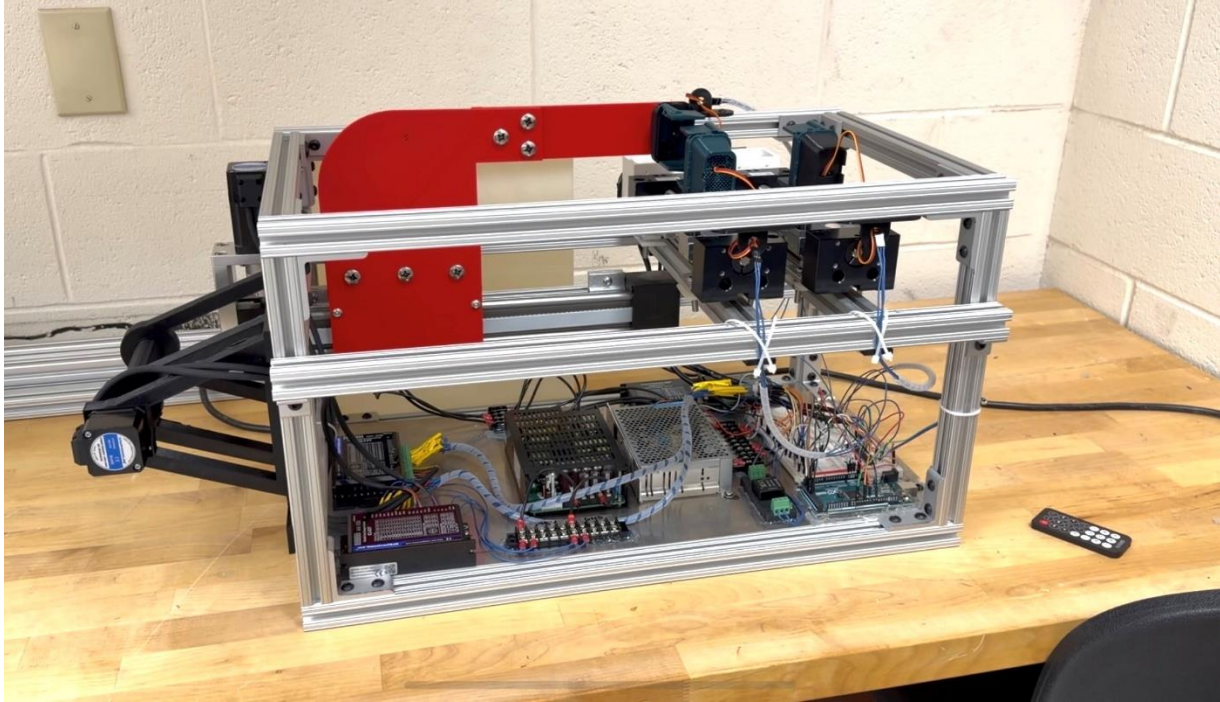


Figure 4: Space Loom Physical Prototype

From the figure above, the mechanical subsystem consists of an aluminum extrusion frame or T-slotted framing. This frame provided structural rigidity and maintained alignment of components during operation. The 3D printed components can also be seen in this image. The red 3D print is the rapier head that transports yarn from the black 3D printed yard holder on the left side of the figure. The grabber mechanisms were also 3D printed (green) and can be seen on the end of the rapier head and on each beat-up linear guide.

During the 3D printing process, our team identified multiple areas for improvement and adjustment. The rapier head itself required multiple 3D prints to maintain structural rigidity while providing the physical footprint necessary to insert yarn into the weft. The grabber mechanisms consisted of not only a frame for the servos, but also 3D printed gears and racks. These 3D printed gears and racks require multiple iterations of 3D print settings inside our slicer and can be seen in Figure 5 below.

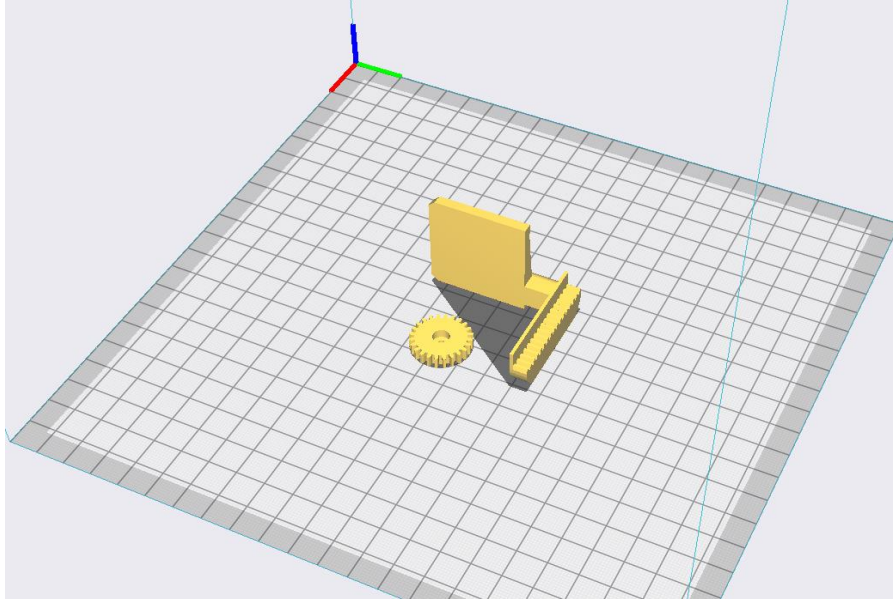


Figure 5: 3D Printed Gears: Slicer UI

From the image in Figure 4, the electrical subsystem can be seen mounted to the base plate at the bottom of the prototype. To illustrate this subsystem further, an electrical wiring diagram was created and is shown below in Figure 6.

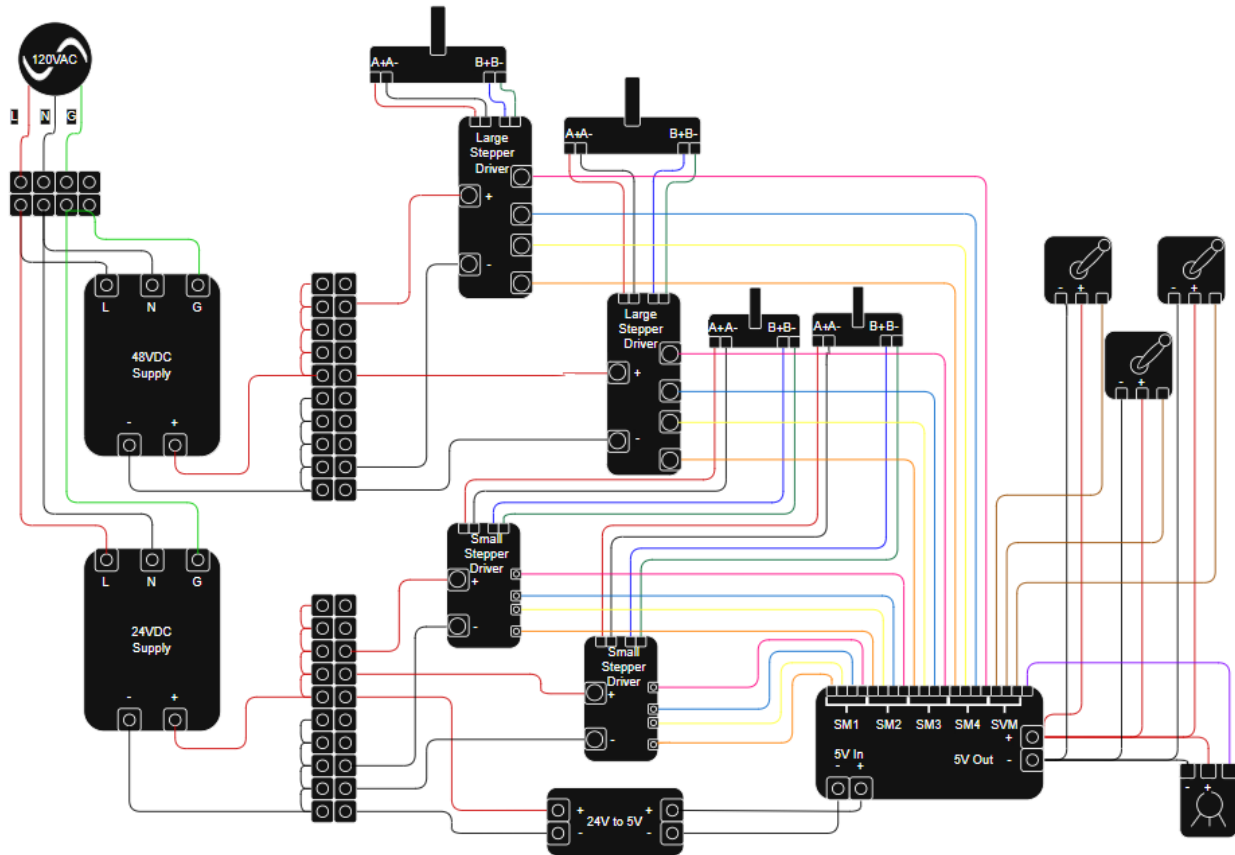


Figure 6: Electrical Wiring Diagram

From the image above, the electrical subsystem contains multiple voltage levels. A 48VDC supply rail and a 24VDC supply rail are generated from a 120VAC supply. The 48V supply is used for higher torque stepper motors and stepper motor drivers. The 24V supply is primarily for smaller, lower torque stepper motors and stepper motor drivers. The 5V supply is then generated via a 24V to 5V DC/DC converter. This 5V supply powers our microcontroller, sensors, encoders, and IR receiver.

Overall, this electrical subsystem provides stable power distribution to run all motors and logic control necessary to function. Our team also used wire harnesses and modular connectors to improve the maintainability and organization of the prototype.

Finally, the system that is embedded within the microcontroller: the software subsystem was responsible for sending controls to stepper motors and servo motors according to the control signal sent via the IR remote. The software employed switch-case statements that would perform a particular action based on the remote IR input. These switch-cases included manual control of all stepper motors and servo motors as well as the ability to play and pause the autonomous control. In order to interface with the stepper motors, the AccelStepper.h library was used which allowed control of speed and steps based on encoder input. The Servo.h library was used to set the angle of the servo motors, and the IRremote.h library was used to read the IR remote inputs.

4.5 Engineering Analysis and Equations

To complete some elementary engineering analysis, a few equations were used to inform the selection of components. These equations assessed power consumption, thread tensions, and motor torque requirements.

The equations used to assess power consumption are shown below.

$$P_{total} = \sum_{i=1}^n P_i \quad (1)$$

$$P_i = I_i^2 R_i = I_i V_i: \text{ power consumption of each component} \quad (2)$$

The primary contributors to this total power were the stepper motors, servo motors, and microcontrollers. Our team also assessed the potential effect on power consumption in the 48V supply, 24V supply, and DC/DC converter as it pertains to their efficiency. Overall, the system is designed to remain below the 300 W sustained power constraint and allow for room for future development of the asset.

The equations used to assess tension in the thread are shown below.

$$T = \frac{F}{A} \quad (3)$$

$$T = \textit{tension} \quad (4)$$

$$F = \textit{applied force} \quad (5)$$

$$A = \textit{cross - sectional area of thread} \quad (6)$$

The disc tensioner servo system would use this equation primarily to regulate the force dynamically based on the torque input from the stepper motors.

The equations used to assess the torque requirement of the stepper motors is shown below.

$$\tau = r * F \quad (7)$$

$$\tau = \textit{torque} \quad (8)$$

$$r = \textit{radius of spool or pulley} \quad (9)$$

$$F = \textit{required force} \quad (10)$$

The use of this equation ensured that the motors were properly sized for the system loads.

5 Mission-Level Impact

The proposed Space Loom system provides a direct advancement in In-Space Servicing, Assembly, and Manufacturing (ISAM) capabilities by introducing the ability to produce textile

materials on demand in a microgravity environment. This capability addresses both near-term operational needs and long-term mission sustainability challenges.

5.1 Immediate Applications and Long-Term Impact

In the near term, this system enables several practical applications that directly enhance mission safety and operational flexibility.

One of the most critical applications is the production of spacesuit repair patches. Current missions rely on pre-manufactured repair materials, which limits the ability to respond to unexpected damage. An onboard textile manufacturing system allows astronauts to produce patches as needed, reducing reliance on stored inventory and increasing mission resilience.

Another key application is the fabrication of thermal insulation materials. Spacecraft and habitats rely heavily on layered textile insulation systems to regulate temperature. The ability to manufacture or replace insulation in orbit allows for maintenance and adaptation of thermal systems over time, particularly for long-duration missions.

Additionally, the system enables the production of flexible structural materials, such as woven reinforcements or protective layers. These materials can be used for temporary repairs, shielding, or structural augmentation, expanding the range of tools available to astronauts and robotic systems.

While the immediate applications of the system are valuable, the long-term impact of this technology could be significantly more transformative to the industry.

The ability to manufacture textiles in space enables a shift toward self-sustaining spacecraft and habitats. Instead of relying on Earth for all consumable materials, space missions can now produce certain components locally. This becomes especially important for deep space missions, where resupply is limited or impossible.

For lunar or Martian missions, this capability will support the development of in-situ resource utilization (ISRU) ecosystems, where materials are produced, repaired, and reused within the mission environment. Textile manufacturing could be integrated into other ISAM systems to create larger structures like protective coverings or habitat layers.

Overall, this technology contributes to the broader goal of modular and adaptable space systems. It represents a foundational step toward sustainable, long-duration space exploration by introducing a new class of manufacturing into the ISAM ecosystem.

5.2 Key Transformation from Today and Storyboard

Traditionally, textiles used in space are treated as consumable cargo. Every patch, insulation layer, or fabric-based component must be designed, manufactured, and launched from Earth. This can create constraints on mission planning, as all potential needs must be anticipated in

advance. The proposed system fundamentally changes this paradigm to on-demand manufactured resource and enable reduced launch mass and volume, increased mission adaptability, and real-time response to damage.

To fully understand the impact of this system, it is useful to consider its role across the entire mission life cycle. The following storyboard in Figure 7 below outlines how the system operates from launch through deorbiting.

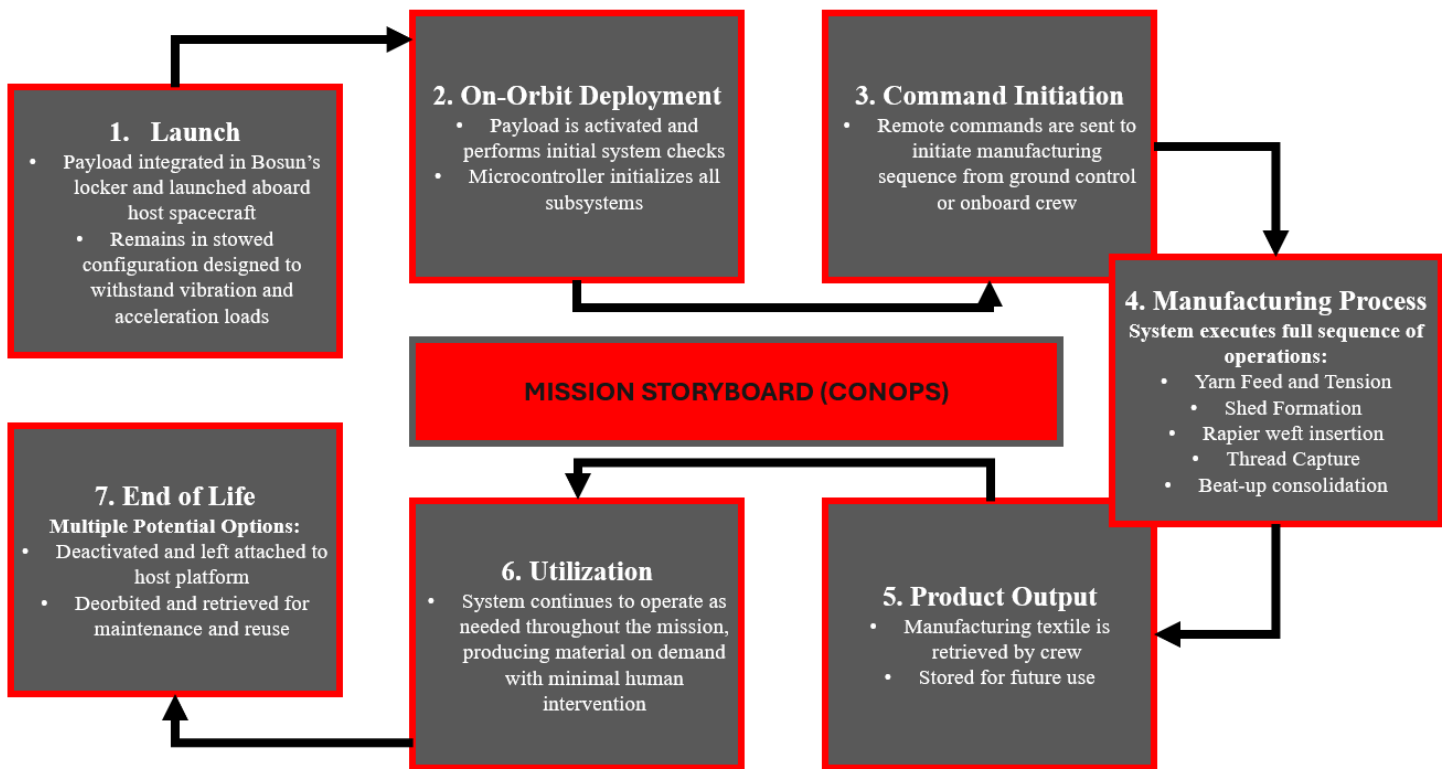


Figure 7: Space Loom Storyboard (CONOPS)

This mission sequence demonstrates that the Space Loom system is not just a standalone experiment, but a functional component of a larger ISAM ecosystem. It integrates seamlessly into the mission lifecycle and provides continuous value throughout operation.

6. Conclusion

This project successfully demonstrates the feasibility of autonomous textile manufacturing in a microgravity environment through the design, analysis, and prototyping of a rapier-based weaving system. The Space Loom system was developed to operate within the constraints of Arkisys' Bosun's Locker while meeting key COSMIC requirements, including power limitations, volume constraints, and the demonstration of a chain of discrete manufacturing operations. Through concept generation and trade studies, a single rapier system with mechanical

grabber handoff was selected as the optimal design due to its balance of reliability, simplicity, and microgravity compatibility. The system architecture integrates mechanical, electrical, and control subsystems into a cohesive platform capable of executing weft insertion, thread capture, and consolidation operations.

A fully assembled prototype was constructed and tested to validate system performance. The prototype demonstrated coordinated multi-axis motion, semi-autonomous operation, and successful execution of the core manufacturing sequence. Validation testing confirmed the system's ability to operate independently of gravity, while also identifying areas for improvement such as tension control and gripper performance. The existence of a working prototype significantly strengthens the feasibility of the proposed system and provides confidence in its scalability toward future development.

Overall, the Space Loom system establishes a foundation for future advancements in orbital manufacturing. With further refinement, including improved tension control, enhanced automation, and expanded material capabilities, this system has the potential to become a critical component of next-generation space infrastructure supporting long-duration missions and extraterrestrial habitation.