# Conceptual Design of In-Space Orbital Reliable Printed Circuit Boards

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**Deep Interstellar Solutions is proposing a device to produce custom, serviceable printed circuit boards (PCBs) in low Earth orbit. This technology uses blank PCBs that are laser-etched and prepared for electrical components, then stored in the module. This method of PCB production enables rapid repairs or prototyping without requiring subsequent resupply missions. By implementing this technique, future missions will achieve greater autonomy, sustainability, and resource efficiency. The goal of this development is to pioneer custom circuitry for deep-space missions where resupply is neither cost-effective nor timely.**

## I. Introduction

In-space servicing, assembly, and manufacturing (ISAM) has become a major focus for government agencies, private companies, and academic institutions. Many of the systems currently in orbit were designed either with the assumption that regular support from Earth would be readily available or with multiple redundancies that increase cost and mass (Rome et al. [1]; Dremann et al. [2]). As mission goals become more complex and more distant from Earth, and mission timelines lengthen, these assumptions and design strategies become impractical and risk mission success. Unexpected failures interrupt mission progress and can endanger human life, underscoring the importance of pursuing ISAM goals (Arney et al. [3]). Recent national ISAM strategies highlight the need for on-orbit manufacturing and production capabilities that reduce dependence on resupply and support operations. Developing systems capable of manufacturing, processing, and assembling hardware within confined orbital environments, such as the Arkisys Bosuns Locker, is a critical step toward deep-space missions and continuous orbital presence.

Modern spacecraft depend on electronic components to operate and communicate, and electronic hardware is particularly difficult to support after launch, as many failures originate at the circuit board level. Printed circuit boards (PCBs) are essential to every spacecraft subsystem, and a single failed board can disable critical vehicle or payload functions. Research on manufacturing in microgravity has demonstrated additive manufacturing, such as 3D printing and polymer processing, and limited machining, but this work has focused primarily on structural components rather than electronics. NASA's In-Space Manufacturing portfolio and On-Demand Manufacturing of Electronics effort specifically identifies on-orbit electronics production and circuit board fabrication as areas requiring significant development (Prater et al. [4]).

Printed circuit boards (PCBs) serve as the essential structural foundation for nearly all electronic systems used in space applications, including satellites, spacecraft, rovers, and launch vehicles. Their significance lies in providing the physical platform and electrical connections necessary for complex systems to operate reliably in the harsh, unforgiving environment of space. They are the central platform for integrating a variety of electronic components, including microprocessors, sensors, communication modules, and power systems. They efficiently route electrical signals and power, reducing the need for bulky, unreliable wiring harnesses (Cauwe [5]).

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Many vital functions in a spacecraft depend on PCBs. Examples relevant to ISAM include maintaining satellite orbits, which require precise control systems; satellite communication systems; computers; scientific instruments; and the management and distribution of power from solar arrays or batteries. Thus, it is required that PCBs in space withstand conditions that would instantly damage commercial electronics. Some crucial conditions include exposure to extreme temperature variations, a vacuum, and high-energy cosmic and solar radiation. Mission failure is not an option when components cannot be easily repaired or replaced. PCBs are built to strict quality standards and thorough testing protocols, and often include redundant systems or backup signal paths to ensure continuous operation. The ability to manufacture replacements in space would be vital (Price [6]; Courtright et al. [7]). PCB manufacturing presents unique challenges in orbital environments due to changes in heat-transfer behavior, debris-control methods, alignment precision and stability, and liquid behavior in microgravity (Hanson et al. [8]; Heltzel et al. [9]). These constraints motivated the team to explore laser-based etching, dry-film solder mask application, and flight-proven material-handling systems that operate reliably within the volume, power, and environmental constraints of the Bosuns Locker while remaining cost-effective.

Deep Interstellar Solutions, the team's name, chose to focus on PCB manufacturing because it represents an important ISAM capability that remains far less developed than structural or mechanical processing, despite its prominent need. Existing work on on-orbit electronics fabrication remains limited in scope, and very few efforts attempt to combine storage, transport, laser etching, solder mask application, and inert-gas debris mitigation within a small, automated system. This gap presents an opportunity to study how fundamental PCB manufacturing processes could be adapted for microgravity, altered heat-transfer behavior, and vacuum conditions. The Conceptual Design of In-Space Orbital Reliable Printed Circuit Boards (ORCA) consisted of a chain-and-sprocket-driven tray system, a laser-etching and debris-expulsion assembly, and a dry-film solder-masking sequence, developed to adapt existing PCB fabrication processes to the constraints of the Bosuns Locker. By addressing a needed capability that remains underdeveloped compared with other forms of on-orbit manufacturing, ORCA and Deep Interstellar Solutions contribute to the broader goal of establishing a foundation for future in-space electronic hardware production systems.

### A. ISAM Program

In-Space Servicing, Assembly, and Manufacturing (ISAM) is rapidly becoming a key focus in both the public and private sectors of the aerospace industry. A renewed commitment to deep space exploration and the growing presence of private space companies, such as SpaceX and Blue Origin, are driving this interest. The ability to assemble, manufacture, or repair equipment in space is gaining traction due to the high costs of resupply missions and the current lack of technology capable of performing these tasks in mission environments. Developing technologies that meet these needs is crucial to the success of future space missions (Trujillo et al. [10]; Malshe et al. [11]; Skomorohov et al. [12]). The recent U.S. National ISAM Implementation Plan outlines the goals set by organizations such as NASA, the U.S. Air Force, and the U.S. Space Force (Rome et al. [1]). It emphasizes the importance of advancing ISAM technologies and assessing existing capability gaps as critical requirements for success in both orbital and deep-space missions moving forward (Rome et al. [13]; Cavaciuti et al. [14]; Arney et al. [15]).

### B. C3: COSMIC Capstone Challenge Overview

The Consortium for Space Mobility and ISAM Capabilities (COSMIC) Capstone Challenge was established by NASA in 2023 in response to the publication of the ISAM National Strategy. The Workforce Development Focus Area (WDFA), a section of COSMIC dedicated to inspiring future aerospace professionals, created the COSMIC Capstone Challenge (C3) to promote the development and interest in ISAM technologies. The 2025 C3 goal is to lay the groundwork for future work in this field. The 2025 objectives are:

1. Develop and test automated systems capable of performing precise, repeatable tasks in the space environment with minimal ground intervention.
2. Demonstrate a multi-step manufacturing chain.
3. Provide a stepping stone into the future of orbital manufacturing and assembly.

These objectives aim to support the initial design work for a complex ISAM mission that could occur by the end of the decade (Agwu et al. [16]).

## C. Mission Description

The COSMIC Capstone Challenge (C3) offers four tracks for teams to choose from, each exploring a key area of ISAM. These include:

1. Track 1 Challenge: Orbital manufacturing and Assembly (C3-Manufacturing)
2. Track 2 Challenge: Lunar Operations (C3-Lunar)
3. Track 3 Challenge: Orbital Servicing (C3-Servicing)
4. Track 4 Challenge: In-Space Assembly (C3-Assembly)

The Deep Interstellar Solutions team decided to pursue Track 1 Challenge: Orbital Manufacturing and Assembly (C3-Manufacturing). This track requires teams to design a payload to be hosted aboard Arkisys' Bosuns Locker. The payload must be capable of semi-autonomously completing three or more distinct operations that provide significant capabilities for ISAM-related missions. This track was chosen because many team members had manufacturing experience and were interested in recent manufacturing-focused ISAM-related projects conducted by public and private space agencies (Agwu et al. [16]).

## D. Project Impact

The ORCA project has the potential to transform the production of electronic hardware in space and significantly enhance the autonomy of deep-space missions by enabling custom, on-demand PCB manufacturing in microgravity environments. This innovation will help reduce the number of resupply missions required to sustain effective deep-space operations, ultimately lowering costs and increasing mission autonomy (Rome et al. [1]; Dremann et al. [2]). The device will enable the creation of customized PCBs for experiments, repairs, or upgrades to existing hardware during missions.

### *1. Aerospace Industry Relevance*

ORCA addresses the manufacturing capability gap between Earth and space. Modern technologies largely rely on PCBs for their functionality. Without the ability to produce these boards during missions, the aerospace industry is forced to rely on prefabricated replacement parts or undertake resupply missions to obtain essential equipment. ORCA enables automated, on-demand PCB manufacturing, saving time, reducing costs, and minimizing manpower requirements. This capability significantly enhances astronauts' operational effectiveness and reduces their dependence on resupply missions under unexpected conditions. Furthermore, it demonstrates the practical application of technology developed to fabricate electronic components in space, underscoring the importance of further exploration in this domain. Ongoing research and testing on semiconductor manufacturing in low Earth orbit are already underway, as the presence of functional circuits is crucial for warranting additional investigation (Salminen and Vesterinen [17]; Lim et al. [18]).

### *2. Student Relevance*

The COSMIC challenge helped the team grasp the crucial role of ISAM in advancing human exploration beyond Earth. ORCA recognized the importance of integrating ISAM considerations into space technology development. It became clear early on that design decisions made in the initial stages of development can significantly affect the project's success if made incorrectly. Furthermore, the COSMIC challenge emphasized the need to stay up to date with cutting-edge technologies. Without thorough research into the latest advancements, many of ORCA's design elements could have failed or taken significantly longer to develop. Ultimately, both ORCA and the COSMIC challenge have inspired team members to pursue careers in the aerospace industry, providing them with insights into the field through interactions with mentors during the COSMIC Capstone Challenge.

# II. Project Description

A sustained presence beyond Low Earth Orbit cannot depend on Earth-based manufacturing for critical components, particularly in PCB-based electronics. Therefore, it is essential to develop and demonstrate a process for manufacturing PCBs in space for long-term human exploration. ORCA was specifically designed to meet this need by utilizing laser-etching technology to autonomously create custom circuits. This etching technique, combined with a conveyor system, solder masking, and storage capabilities, enables ORCA to produce up to 10 PCBs per mission. These PCBs can serve as replacement parts, custom circuits for experiments, or fulfill other necessary functions to support mission objectives. This innovative approach not only reduces reliance on complex supply lines for deep-space missions but also minimizes the number of spare parts required and enhances operational autonomy. Although ORCA was designed to operate within the constraints of the Arkysis Bosuns locker, this technology can be scaled to meet the needs of future missions, thereby supporting deep-space exploration.

## A. Management Plan

Deep Interstellar Solutions is composed of five undergraduate students who are enrolled in the mechanical engineering program and are simultaneously pursuing a Minor in Aerospace Engineering at Kennesaw State University. The team is guided by a professor serving as the principal investigator and a mentor from the Aerospace Corporation. Figure 1 provides a summary of the management plan.

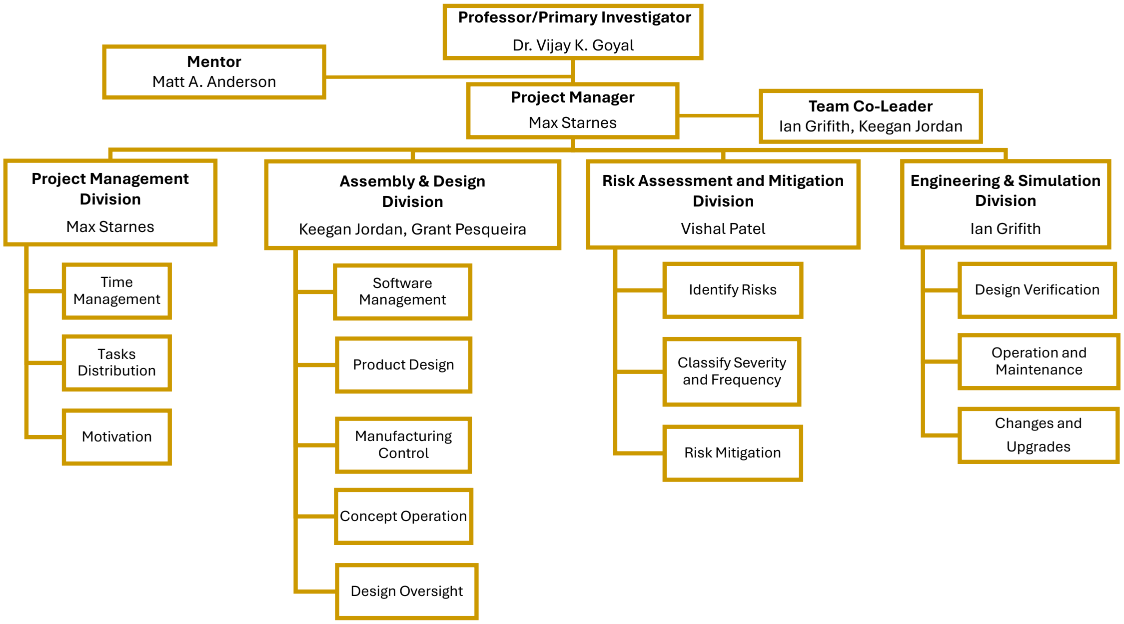


**Fig. 1 Management Plan**

## B. Mission Conceptual Review

This project aims to create a system for the semi-autonomous manufacturing of printed circuit boards (PCBs) in space. The objective is to reduce reliance on Earth-based manufacturing, enable on-demand production, support part customization, and prioritize time efficiency over cost efficiency in space.

### *1. Objective and Goals*

The objective of this project is to develop a system that can semi-autonomously manufacture printed circuit boards within the confines of a single Bosun's Locker.

1. The storage must securely hold processed materials during fabrication. Additionally, dispenser and storage units

must be created to contain printed circuit boards before and after etching.
2. The manufacturing process will use a conveyor system that moves printed circuit boards horizontally between various systems. Software tools will be installed on dedicated systems to interpret electrical designs from user input.
3. The system will include methods for verifying processes. It will confirm the functionality of components and the quality of process completion.

## *2. Assumptions*

The success of this endeavor lies upon several key assumptions that form the foundation of our approach:

1. PCB blanks are designed to operate and be laser-etched under harsh environmental and vacuum conditions.
2. The power supply and data communication interfaces are supplied externally by the host spacecraft.
3. No human intervention is needed during normal operation once remote activation and parameter settings are complete.
4. No human intervention is needed during normal operation once remote activation and parameter settings are complete.
5. Overall stress will be lower than the worst-case simulation. The system underwent testing under sea-level gravity and simultaneously at extreme orbital temperatures.
6. Vacuum conditions will be assumed during the entire design and analysis process.

## *3. Project Tasks*

The success of this project can be largely credited to a variety of influential factors:

1. **Project Management:** The team leaders defined overall objectives, outlined each member's responsibilities, established timelines, and brainstormed methods to ensure efficient task completion. They allocated resources, set deadlines, and defined clear project goals.
    a) **Time management:** The team lead was responsible for managing this part of the project. Effective time management involves evaluating weekly, monthly, and semester-long goals and assigning tasks based on team members' availability. After this assessment, schedules were created to establish delivery deadlines, ensuring that the project remained on track and that sufficient time was allocated for peer review of all deliverables.
    b) **Cost management:** At the start of the project, an initial estimate of the overall costs was created, along with a budget for financial expenses. This budget encompassed costs for Commercial Off-The-Shelf (COTS) components, custom components, labor, and other expenses. The budget was considered during component selection, and a final financial analysis was conducted to ensure budgetary goals were met.
2. **Laser-etching Technology Review:** The laser-etching component of ORCA is likely its most critical feature. One of the primary objectives of DIS was to evaluate available technologies and assess their applicability to the specific environmental and operational conditions that ORCA will encounter.
    a) Environment: An evaluation was conducted on various laser systems and their performance in vacuum conditions or low-gravity environments. The team also examined the power consumption associated with these conditions. Trade studies were used to assess each component, enabling us to make informed decisions about which technologies would be most suitable for ORCA.
    b) Uses: To identify the most suitable technology for ORCA, the team began by thoroughly understanding the device requirements. Next, the team evaluated the materials that would be etched and the performance of each laser. This process led us to eliminate several devices from consideration.
3. **PCB Storage and Conveyor System Development:** The main function of ORCA is to etch circuits, but it is also essential to store both blank and completed PCB boards to achieve this goal. This aspect was a significant consideration throughout the project, leading to some of the greatest challenges and most innovative solutions.
    a) Storage: Designing a secure storage solution for PCB boards, both before and after etching, was crucial. It was vital to create a system that could fit within the dimensions of the Bosuns locker.
    b) Conveyor System: The conveyor system must transport PCBs from storage through the device to the secondary storage magazine. This task is challenging in zero gravity and requires careful consideration of multiple factors to create an effective solution.

4. **Risk Assessment and Mitigation:** Understanding the potential risks related to individual components and subsystems can help in developing solutions that effectively address issues based on their severity during the production cycle. In this context, risk is evaluated with respect to both human safety and mission success.
    a) ORCA risks: The ORCA system encounters various technical and operational risks that could negatively affect PCB manufacturing in microgravity conditions, have repercussions on other lockers within the Arkisys module, or potentially lead to human harm. All of these factors have been thoroughly considered. The identified risks include: mismanagement of debris, failure of the solder mask to properly bond to the PCB, dry-film solder mask feed errors, deviation of the laser path during etching, thermal hot-spot formation during laser etching, mechanical jamming or chain slip in the conveyor, contamination of the conveyor assembly, misalignment of the PCB trays on the conveyor surface, nitrogen supply pressure loss, and initialization or reset errors during system startup. Addressing these risks is crucial to ensuring the safety and efficiency of the ORCA system.
    b) Classification and Approach: The team generated, reviewed, and validated the methodologies across all subsystems. The risks are captured in a probability table, in which the likelihood of each risk occurring is compared with its potential impact. Every risk has an associated mitigation approach. The following approaches are used: localized nitrogen purge of debris, control of solder mask lamination, control of solder mask feed alignment, path verification, PCB tray position verification, thermal management, pressure monitoring, tension and slip monitoring, tray shielding, and startup validation. As a result, if potential risks are identified in the prototype phase, the mitigation approach provides a general guideline for reducing overall risk.
5. **Simulations & Testing:** The team finalized the ORCA system design to assess the mechanical, thermal, and operational loads expected in microgravity conditions. Each subsystem will undergo engineering analysis to evaluate its characteristics, functionality, trade-offs, and potential failure modes. This model aims to examine structural integrity, thermal behavior, and mechanical performance under extreme environmental conditions. Finite element analyses were performed for the following subsystems: frame, PCB trays, dispenser and storage assembly, laser etcher and debris-expulsion unit, and solder-masking components. A combination of static loading and extreme thermal conditions will be applied to determine the first principal stress, displacement, and strain for each component, to assess structural integrity. The designs for the power screw and conveyor chain assembly mechanisms were also developed to meet torque requirements, frictional loading, and chain speed. All simulations considered worst-case scenarios, including full shadow and direct sunlight, Earth's gravity, and the maximum PCB load capacity. The simulation and testing efforts helped evaluate each subsystem's structural and thermal performance, as well as possible failure modes, for the final design.

## C. System Requirements Review

### *1. System Overview*

The Conceptual Design of In-Space Orbital Reliable Circuit Boards (ORCA) is designed to fabricate printed circuit boards in orbital environments, facilitating autonomous spacecraft maintenance and on-demand manufacturing. The system comprises five primary subsystems: a storage unit for both blank and completed PCB boards, a laser-etching unit for the manufacturing of circuit boards, a solder masking unit that applies a solder mask film on the etched boards, a conveyor system that transports the blank and completed boards through the machine, and a debris mitigation system that prevents device failure by eliminating particulates generated during the etching process.

### *2. System Requirements*

1. System shall manufacture PCBs in orbit.
    1A. System shall be able to manufacture 10 PCBs before being restocked.
    1B. The system shall be able to operate without physical human input beyond its initial setup.
    1C. System shall be able to process/interpret circuit diagrams, manufacture completed boards, and test functionality.
    1D. The system shall be capable of securing completed PCB assemblies.

2. The system shall collect any dust or debris from the manufacturing process.
    2A. The system shall collect dust generated during manufacturing.
3. The System shall operate under the specified conditions of the Bosuns Locker.
    3A. The system shall operate at 5-28 V and less than 300 W for standard operation.
    3B. System shall be no larger than 144,145 $cm^3$ and have a center of gravity 17.5 cm from a BL-S/C Interface Panel.

### 3. Environment Requirements

1. The system shall be able to operate in low Earth orbit.
    1A. The system shall maintain low outgassing levels under vacuum conditions.
    1B. The system shall withstand exposure to cosmic and solar radiation without functional degradation.
    1C. The system shall maintain electrical performance and structural integrity in microgravity environments.
2. The system shall be able to operate in extreme thermal environments.
    2A. The system shall operate at a maximum operating temperature of 394 K.
    2B. The system shall operate at a minimum operating temperature of 148.15 K
    2C. The system shall dissipate internally generated heat effectively to stay within component safety limits.

### 4. Manufacturing Requirements

1. The system shall be able to withstand mechanical forces.
    1A. The system strength shall exceed 10 MPa.
    1B. The system strain shall be less than 5 $\mu$m/mm.
2. The system shall be adaptable.
    2A. The system shall contain 60% commercial-off-the-shelf components.
    2B. The system shall have three remotely adjustable DOF.

### 5. Design Requirements

1. The system shall be cost-effective.
    1A. The system shall cost less than twenty thousand dollars.
2. The system shall be able to fit into the dimensions of a Large Bosuns Locker.
    2A. The system shall fit within the usable payload area of 144,145 $\text{cm}^3$.
3. The system shall be able to operate with the power supplied to the Bosuns locker.
    3A. The system shall be capable of operating with a 300 W power pass-through.
    3B. The system shall operate between 5 and 28 V.
4. The system shall not launch debris in space.
    4A. System shall release no debris into space.
5. The system shall have a long service life.
    5A. The system shall have a service life of one year.
6. The system shall be able to secure pre- and post-manufactured materials.
    6A. The system shall store 10 PCB blanks.
    6B. The system shall be capable of storing 10 manufactured PCB assemblies.
    6C. The system shall secure assemblies at each manufacturing step.
7. The system shall be accurate and repeatable.
    7A. System shall maintain accuracy in reference to the technical drawings within 100 $\mu$m.
    7B. System shall maintain consistent results.

### 6. Operation Success Criteria

The success criteria for the system operation are as follows:

1. System Performance
    1A. The system must manufacture 1 PCB within 20 minutes.

2. Accuracy
    2A. The system must produce accurate results in accordance with the PCB technical drawings.
3. Reliability
    3A. The system must maintain repeatable results.
4. Maintainability
    4A. All system components must be designed for maintenance within 4 hours.
5. Modularity
    5A. The system should be designed to integrate with other systems on the Arkisys.

## III. Conceptual Designs

The team considered six distinct design concepts, each aligned with seven design criteria, as shown in Table 1. These seven design criteria are weighted individually, as shown in Table 2, to rank the extent to which each design addresses these parameters, as reflected in the final decision matrix.

**Table 1 Criteria Definitions**

| Design Criteria | Description | Parameters | More or Less? |
|---|---|---|---|
| **Simplicity** | Quantity and complexity of components | N/A | Less |
| **Autonomy** | Quantity and complexity of human input required for operation | No. of Inputs: 2 | Less |
| **Size, Weight, and Power (SWaP)** | Total volume, weight, and wattage consumed | Max Mass: 400 kg<br>Max Power: 300 W<br>Max Vol: 144,145 $\text{cm}^3$ | Less<br>Less<br>More |
| **Price** | Program cost (R&D, AI&T, Operations) | ~20,000 USD | Less |
| **Manufacturability** | Prototype and PCB manufacturing time, tolerances, quality, process efficiency | N/A | Less |
| **Durability** | Resistance against mechanical strength | Strength: 10 MPa<br>Strain: 5 μm/mm | More |
| **Adaptability** | Quantity of COTS components and number of DOF accessible for remote manipulation | 60% COTS<br>No. of DOF: 3 | More |

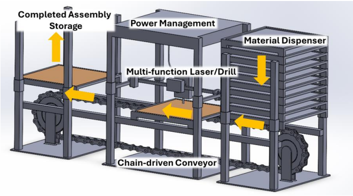
**Table 2 Ranking design criteria using the weighted approach**

| Design Criteria | Simplicity | Autonomy | SWaP | Price | Manufacturability | Durability | Adaptability | Weight |
|---|---|---|---|---|---|---|---|---|
| **Simplicity** | - - - | 0.5 | 1 | 1 | 0.5 | 0 | 0.5 | **17%** |
| **Autonomy** | 0.5 | - - - | 1 | 1 | 0.5 | 1 | 1 | **24%** |
| **SWaP** | 0 | 0 | - - - | 0.5 | 0 | 0 | 0 | **2%** |
| **Price** | 0 | 0 | 0.5 | - - - | 0.5 | 0.5 | 0 | **7%** |
| **Manufacturability** | 0.5 | 0.5 | 1 | 0.5 | - - - | 1 | 0.5 | **19%** |
| **Durability** | 1 | 0 | 1 | 0.5 | 0 | - - - | 0 | **12%** |
| **Adaptability** | 0.5 | 0 | 1 | 1 | 0.5 | 1 | - - - | **19%** |
| | | | | | | | | **100%** |

0.0 – Not impactful
0.5 – Somewhat impactful
1.0 – Most impactful

$$\text{Weight} = \frac{\text{Criteria Score}}{\text{Total Score}}$$

## A. Conceptual Design 1



| Criteria | Rank | Advantage | Disadvantage |
|---|---|---|---|
| **Simplicity** | +2 | Minimal moving parts.<br>**Four** moving component systems.<br>**60-70** parts per unit. | Gantry system (magnets).<br>Multi-step storage. |
| **Autonomy** | +2 | Fully autonomous. | |
| **SWaP** | 0 | Fills available volume.<br>Skeletonized design. | Chain takes up excessive space.<br>High power draw. |
| **Price** | +2 | Utilizes all COTS parts.<br>Overall program cost of **~10,000 USD.** | Many servos. |
| **Manufacturability** | +1 | Simple construction, geometry, and COTS parts.<br>Laser and integrated router enabling high procession.<br>Run time of **12 hr**. | Complex tool head. |
| **Durability** | –1 | | Skeletonized design with stress concentration points.<br>Chain and sprocket meshing becomes difficult with large temperature swings. |
| **Adaptability** | +1 | **75% COTS Parts / 3 DOF** | |

+3 = BETTER
0 = NO FACTOR
–3 = WORSE

**Fig. 2 Assessment of conceptual design 1.**

Conceptual Design 1, illustrated in Figure 2, employs a laser etching module to engrave trace designs onto copper, eliminating the need for chemical etching. Pre-cut 6×6-inch copper blanks are placed in individual trays and loaded into a material dispenser. When the manufacturing process begins, the material dispenser lowers the stack of trays onto the conveyor system using a series of stepper motors and power screws. The dispenser will release one tray onto the conveyor and then lift the remaining trays back into storage.

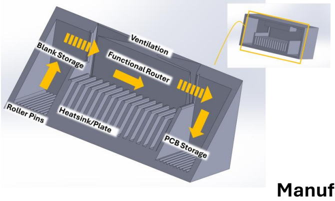
The conveyor system consists of a chain and sprockets, powered by a stepper motor, to transport the tray containing the copper blank along the manufacturing line. As the tray enters the work area, a multifunctional tool equipped with both a laser-etching module and a drill module will etch the desired design into the copper and drill holes for future circuit components. This tool is mounted on a three-degree-of-freedom gantry powered by additional stepper motors, power screws, and belts. Once the operation is complete, the conveyor will move the assembly to the completed material storage area. The gantry, also powered by stepper motors and power screws, will lower to pick up the tray with the completed assembly and move it into storage.

Conceptual Design 1 performed well across most evaluation criteria, though some limitations prevented it from achieving higher scores. In terms of simplicity, the design earned a score of +2 due to its extensive use of COTS components and its minimalist approach. It did not receive a higher score due to the complexity of the magnetic gantry system. For the autonomy criterion, this design received a score of +2, as it operates fully autonomously after startup and requires minimal preparation beforehand. It did not score higher because its effectiveness was not measurably superior to the baseline parameter. Regarding SWaP, Conceptual Design 1 scored a +0. Although it is small and lightweight, this is viewed as a disadvantage because it does not utilize the maximum allowable volume or weight capacity of the Bosuns locker. Additionally, it draws significant power from the numerous electrical components, yet it remains within the locker's maximum power specifications.

With respect to the price criterion, the design was considered favorable due to the high number of COTS components, which are generally cheaper than custom-fabricated parts. However, the design also incorporates specialized motors for controlling the gantries and conveyor system. For these reasons, it received a +2 score in the price category. This design can accommodate a large number of PCB blanks and is efficient to produce with COTS components. Moreover, laser etching can, in theory, produce highly detailed circuits. Unfortunately, the tool head's complexity significantly affects the device's manufacturability, resulting in a +1 score in this category. In terms of durability, the lightweight, skeletonized design received a score of −1 due to concerns about its fragility. Finally, in terms of adaptability, this design was rated in the middle range, with a similar number of COTS parts to other designs and three degrees of freedom. As a result, it received a +1 score for adaptability.

When these scores were weighted, Conceptual Design 1 ultimately received a total ranking of +122.

## B. Conceptual Design 2



+3 = BETTER
0 = NO FACTOR
−3 = WORSE

| Criteria | Rank | Advantage | Disadvantage |
|---|---|---|---|
| **Simplicity** | −2 | | Large number of small moving parts. |
| **Autonomy** | +1 | Fully autonomous. | |
| **SWaP** | 0 | Fits within the volume. | |
| **Price** | +1 | **~15,000 USD** development cost. | Small components requiring high precision increase manufacturing cost. |
| **Manufacturability** | +2 | Integrated fan and mobile tool suite allow for tight tolerances. Improved heat dissipation. | Small parts require significant assembly. |
| **Durability** | +3 | Robust unibody shell. | |
| **Adaptability** | 0 | **65% COTS / 3 DOF** | Large number of small custom parts. |

**Fig. 3 Assessment of conceptual design 2.**

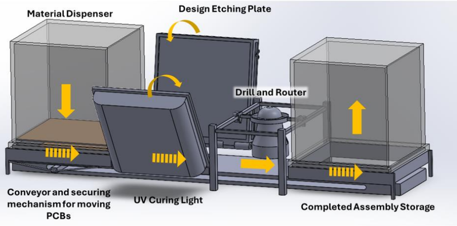
Conceptual Design 2, as illustrated in Figure 3, outlines a PCB manufacturing line that employs roller bearings to move material throughout the system. These roller bearings transport the copper blank from the storage area and flip it onto the heatsink plate. Once placed on the heatsink plate, a multitool mounted above it centers the material in the work area, where clips secure it. The multitool then switches to its router function, etching the desired trace design into the copper blank. During etching, an integrated fan recirculates an inert gas throughout the system to remove debris generated by the etching process from the mechanical components. After etching, the multitool picks up the finished assembly and moves it to the storage area, where another series of roller bearings grabs and stores it.

Conceptual Design 2 received a strong ranking but had critical flaws that prevented its selection. On the first ranking criterion, simplicity, it scored poorly at −2 due to the large number of small moving parts required for its functionality. The roller-bearing system used to move the PCBs was overly complex, with numerous small components prone to failure, thereby hindering the overall design. For the second criterion, autonomy, the device met expectations and was fully autonomous; however, it did not rank particularly high because it lacked task verification features, resulting in a score of +1.

In terms of SWaP, Conceptual Design 2 received a score of 0. While the device met the requirements, its performance on this metric was unremarkable. The design scored +1 on the price criterion, being approximately 25% under budget; however, it could not score higher due to cost increases associated with numerous small, likely custom components. For manufacturability, the design achieved a score of +2, thanks to the precision provided by its multifunction router and heatsink workplate, which enabled very tight manufacturing tolerances. Nonetheless, it did not receive a maximum score due to the number of small moving components. Conceptual Design 2 excelled in durability, earning the maximum score of +3 due to its robust unibody construction, which enhanced its endurance and resilience. For the final criterion, adaptability, the design received a neutral score (0). Although it met the requirements, it did not perform exceptionally well, primarily due to the large number of custom components, which hindered its adaptability.

When these scores were weighted, Conceptual Design 2 ultimately received a total ranking of +71. Overall, it ranked third, following only Conceptual Design 1 and the selected hybrid design of Conceptual Design 6. Its greatest strength was its robust durability, while its most significant drawback was the complexity of its storage mechanisms.

### C. Conceptual Design 3



+3 = BETTER
0 = NO FACTOR
–3 = WORSE

| Criteria | Rank | Advantage | Disadvantage |
|---|---|---|---|
| **Simplicity** | −1 | Each part of the system has an isolated function. | High number of parts. |
| **Autonomy** | +1 | Fully autonomous | |
| **SWaP** | +1 | Uses less than **300 W**.<br>Lightweight design. | Does not efficiently utilize space. |
| **Price** | +2 | **~10,000 USD** | |
| **Manufacturability** | 0 | Simple construction and geometry lead to ease of manufacturing. | Cannot etch copper plating or apply solder mask |
| **Durability** | −1 | | High number of parts lead to more POF.<br>Minimal support structure. |
| **Adaptability** | −1 | **3 DOF** | **45% COTS** |

**Fig. 4 Assessment of conceptual design 3.**

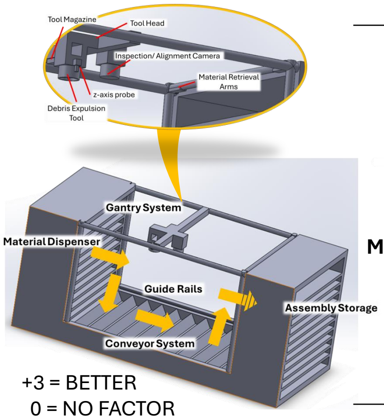
Conceptual Design 3, illustrated in Figure 4, outlines a PCB manufacturing line that replicates the process commonly used by hobbyists to create printed circuit boards (PCBs) at home, but adapts it into an autonomous manufacturing line. Pre-cut 6×6-inch copper blanks must be loaded into the material dispenser manually before startup. Once started, the copper blanks are lowered one by one onto the conveyor system, where a securing mechanism holds them in place. The PCBs are then transported to the first work area via a power screw connected to the conveyor.

The first work area consists of a design etching plate and a UV curing light. The design etching plate is a glass enclosure filled with electrostatically charged aluminum powder. A small magnet on a three-axis gantry traces the desired PCB traces into the aluminum powder, much like an Etch A Sketch. The design etching plate is then returned to its original position, leaving the glass enclosure with a template on top of the copper blank. The UV curing plate is lowered onto the glass enclosure, where three UV lights cure the copper areas of the copper blank not covered by the aluminum powder. After curing, the UV curing light and the glass enclosure of the design etching plate are returned to their original positions. The copper blank then moves to the second work area, where the drill and router gantry cut the PCB to size and drill holes for future electrical connections. The completed PCB is then moved to the completed assembly storage area, where it detaches from the conveyor and is raised into storage.

Conceptual Design 3 received a mixed ranking across design criteria, with several weaknesses outweighing its strengths. It earned a score of −1 for simplicity: although each component performs a single function, the system relies on numerous moving parts, reducing overall simplicity. It received a +1 for autonomy, as it operates fully autonomously after startup; however, this only meets the baseline requirement, which is why it did not score higher. In the SWaP category, it received a +1 for its low power consumption and lightweight frame, though it does not utilize all available space in the Bosuns locker. The design performed best in terms of price, receiving a +2 for being $10,000 under budget. In manufacturability, it received a score of 0. At the same time, the straightforward construction makes custom parts easier to produce; however, this benefit is offset by the system's inability to etch copper or apply solder mask.

Durability was another weak point, earning a −1 due to the large number of components and minimal support structures, which increases the potential for failure. The design also received a −1 for adaptability, as while achieving three degrees of freedom is an advantage, it is outweighed by the number of custom parts required to build the system. When these scores were weighted, Conceptual Design 3 ultimately received a total ranking of −8.

## D. Conceptual Design 4



+3 = BETTER
0 = NO FACTOR
–3 = WORSE

| Criteria | Rank | Advantage | Disadvantage |
|---|---|---|---|
| **Simplicity** | −2 | Simple parts. | Many moving parts and subsystems needed for precision. |
| **Autonomy** | +2 | Verifies design with onboard camera. | |
| **SWaP** | +1 | Router uses less power than laser. | Utilizes space poorly. |
| **Price** | +2 | **~12,000 USD** | |
| **Manufacturability** | −2 | | Only capable of dry routing PCBs.<br>No resist.<br>Complex gantry. |
| **Durability** | +2 | Rigid frame and tube structure. | |
| **Adaptability** | +1 | **70% COTS / 3 DOF** | |

**Fig. 5 Assessment of conceptual design 4.**

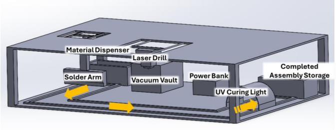
Conceptual Design 4, illustrated in Figure 5, outlines a PCB manufacturing line that uses a toolhead equipped with a small end mill to remove unnecessary material from the copper blank to create the required design. Copper blanks are initially stored in a vertically oriented bay located at one end of the device. A vertically traveling arm retrieves a copper blank from storage and positions it into alignment grooves along the bottom-mounted conveyor. The conveyor then advances the copper blank into the work area beneath the toolhead assembly. At this station, a combined drill-and-end-mill spindle machine drills holes and traces designs into the copper layer of the blank. An integrated debris-mitigation hood captures debris generated by the toolhead through inert-gas expulsion and vacuuming. After machining is complete, an inspection camera mounted on the toolhead inspects the boards to verify the accuracy and alignment of the machined features, with a tolerance of 100 $\mu$m. Once verification is complete, the conveyor moves the finished, validated boards along the side alignment rails to the storage area, where a second vertically traveling arm retrieves the board and stores it in the finished assembly storage area.

Conceptual Design 4 received a mixed ranking across various design criteria, with several weaknesses outweighing its strengths. While the design utilizes relatively simple or commercially available components, it received a score of −2 for simplicity due to its reliance on numerous moving parts and tightly integrated subsystems to achieve the required precision. The design received a +2 autonomy score for incorporating an onboard inspection camera to verify completed assemblies. In terms of SWaP, the design received a +1 since the routing and milling processes consume less power than a laser-based system; however, it does not efficiently utilize the internal volume of the Bosuns locker. For manufacturability, the design received a score of −2 due to its limited processing capabilities and the complexity of its subassemblies. Additionally, the system lacks the capability to apply a solder mask, and the gantry complicates device fabrication and assembly.

Conversely, Conceptual Design 4 received a +2 for durability due to its rigid frame and tubular structure, which provide significant resistance to mechanical deformation and vibration under launch and operational loads. The design earned +1 for adaptability due to its extensive use of commercial off-the-shelf components. However, it lacks modularity and the ability to readily expand or reconfigure the device to accommodate additional steps in the PCB manufacturing process. When these scores were weighted, Conceptual Design 4 ultimately received a total ranking of +35.

## E. Conceptual Design 5

Conceptual Design 5, illustrated in Figure 6, outlines a semi-autonomous PCB manufacturing line that requires some human interaction for transporting copper blanks between workstations. Copper blanks are manually retrieved from the material dispenser and prepared with an externally supplied solder masking gel. After applying the solder mask, the blanks can be placed on the conveyor system. This system comprises a series of belts and rollers that transport copper blanks to their designated locations. A railing system maintains the alignment of the copper blanks on the conveyor throughout manufacturing. The first work area on the conveyor includes a laser and a multitool drill, which etch traces



+3 = BETTER
0 = NO FACTOR
–3 = WORSE

| Criteria | Rank | Advantage | Disadvantage |
|---|---|---|---|
| **Simplicity** | +1 | Minium moving parts, total of **four** moving component systems. | Hand placement storage. |
| **Autonomy** | –3 |  | Semi-autonomous at the beginning and end. |
| **SWaP** | –1 | Lack of excessive non-structural components. | All volume presented it not used effectively. |
| **Price** | 0 | **~ 20,000 USD** | Conveyor system. |
| **Manufacturability** | –2 | UV solder mask and UV curing light.<br>Vacuum system between solder arm and laser drill. | No heat resistance.<br>Human interaction is inefficient. |
| **Durability** | –1 |  | Wear and tear on solder arm and extensive heating. |
| **Adaptability** | –1 | **65% COTS** | **2 DOF** |

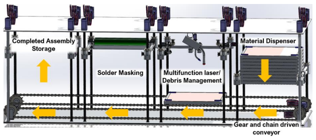
**Fig. 6 Assessment of conceptual design 5.**

into the copper blank and drill the necessary holes for future circuit components. After this step, the conveyor transfers the copper blank to the UV curing station, where UV light cures the solder mask gel. Once the circuit board is complete, it must be manually transferred to the storage area for completed assemblies.

Conceptual Design 5 was evaluated against multiple design criteria, yielding a ranking that reflects its strengths and weaknesses. It received a +1 for simplicity, given its few moving parts. However, the need for extensive manual handling of copper blanks to and from storage disrupted the manufacturing process, adversely affecting its overall score. Consequently, this design received a −3 for autonomy. In terms of SWaP, the design scored −1 because it did not effectively utilize the available volume in the Bosuns locker. It received a score of 0 for price: although it was within budget, the complexity of the expensive conveyor system significantly increased the overall cost. For manufacturability, the design received a score of −2. Although its simple construction and straightforward processes are advantageous, the necessity for human intervention made it impractical for the intended application.

Regarding durability, the design received a score of −1 due to concerns about wear and tear on neighboring components, particularly the conveyor, resulting from the lack of heat shielding on the laser system. Additionally, it received a score of −1 for adaptability due to its non-modular design and limited workspace, which provides only 2 degrees of freedom. When these scores were weighted, Conceptual Design 5 ultimately received a total ranking of −126.

### F. Conceptual Design 6



+3 = BETTER
0 = NO FACTOR
–3 = WORSE

| Criteria | Rank | Advantage | Disadvantage |
|---|---|---|---|
| **Simplicity** | +1 | Minimal number of moving parts.<br>Gear driven system.<br>Modular. | **Six** moving component systems. |
| **Autonomy** | +3 | Fully autonomous once started.<br>Verifies accuracy after manufacturing – conductivity. |  |
| **SWaP** | +2 | Design utilizes all available space in locker.<br>Lack of excessive non-structural components. | Draws high power. |
| **Price** | +1 | **~20,000 USD.**<br>More complete PCB. |  |
| **Manufacturability** | +3 | Will be capable of manufacturing completed unit within **20 mins.**<br>Completes additional processes.<br>High precision from separating process steps into modules. |  |
| **Durability** | 0 | Robust structure capable of withstanding **10 MPa** compression. |  |
| **Adaptability** | +2 | **85% COTS / 3 DOF** |  |

**Fig. 7 Assessment of conceptual design 6.**

Conceptual Design 6, illustrated in Figure 7, combines features from previous concepts into a collaborative design. Pre-cut copper blanks are placed in individual trays equipped with retaining clips to prevent movement during manufacturing. These trays are then loaded into the material dispenser. Once manufacturing begins, a series of stepper motors drives the power screws, lowering the stack of PCB trays onto the conveyor system. When the first tray is released onto the conveyor, a mechanism on the bottom of the PCB tray locks around the chain, preventing any unintended movement. The material dispenser then lifts the remaining trays back into storage.

The conveyor system consists of two sets of sprockets and chains, powered by stepper motors, which transport the tray loaded with a copper blank throughout the manufacturing line. As the tray enters the first work area, a multifunctional laser etching module etches the desired trace design and through-holes into the copper. This tool is mounted on a gantry system that provides three degrees of freedom for precise etching. During etching, a debris-management system behind the laser etching module blows an inert gas into the work area to remove debris from mechanical components. A filtration system at the front of the assembly captures debris and recycles the inert gas for reuse.

After the initial etching is complete, the assembly moves to the next work area for solder masking. The solder masking assembly employs rolls of dry solder mask and thermal printing to uniformly coat the etched copper blank with solder mask. Once the solder masking is complete, the assembly returns to the first work area, where the laser multitool is used again to remove excess solder mask and cut the boards per design specifications. Finally, the conveyor system transports the completed PCB board to the finished assembly storage area, where a gantry system retrieves the tray from the conveyor and raises it into storage.

Conceptual Design 6 performed well across most criteria by incorporating ideas from previous concepts. For simplicity, it received a score of +1 because it uses duplicate gantry systems for all work and storage, keeping the system as straightforward as possible. However, this design did not rank higher because multiple moving components were present in each of the six systems, increasing overall complexity. In terms of autonomy, this design achieved a score of +3, the highest possible ranking, because it can autonomously manufacture ten ready-to-use PCBs before requiring a refill after startup. For the Size, Weight, and Power (SWaP) criterion, Conceptual Design 6 efficiently utilizes the available volume of the Bosuns locker but also draws a significant amount of power from it. As a result, it received a SWaP score of +2. Regarding cost, the initial estimate indicated that this design would use the entire available budget but would produce a PCB that exceeded the original project goals. Therefore, it was assigned a score of +1 for price.

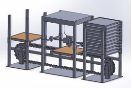
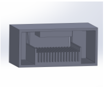
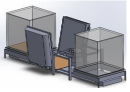
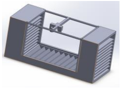
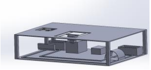
Conceptual Design 6 received a +3 manufacturability score because it can produce a complete PCB within 20 minutes. For durability, it received a neutral score of 0; while the design can withstand the stresses outlined in the criteria, it did not surpass those expectations. Lastly, for adaptability, the modular design enables it to handle manufacturing failures. Additionally, it contains a high percentage of commercial off-the-shelf (COTS) components, making it straightforward to replace worn or broken components. For these reasons, Conceptual Design 6 earned a score of +2 for adaptability.

When these scores were weighted, Conceptual Design 6 ultimately received a total ranking of +195.

### G. The Selected Conceptual Design

Table 3 presents the assigned weights for each design requirement. The design matrix used the Pugh Matrix, also known as the Decision Matrix or Selection Matrix (Guler and Petrisor [19]). This criteria-based tool facilitates the comparison and evaluation of multiple design options against a set of established criteria. Following this evaluation, design option six was selected for its high level of subsystem integration. It incorporates refined elements from previous design iterations while reducing mechanical complexity. Additionally, this design is optimized to fit within the Arkysis Bosuns Locker's volume constraints, unlike earlier design concepts.

**Table 3 Ranking design criteria using the weighted approach.**

| | |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| **Metrics** | **Weight (%)** | **Design 1** | **Design 2** | **Design 3** | **Design 4** | **Design 5** | **Design 6** |
| **Simplicity** | 17 | +34 | −34 | −17 | −34 | +17 | +17 |
| **Autonomy** | 24 | +48 | +24 | +24 | +48 | −72 | +72 |
| **Size, Weight, and Power (SWaP)** | 2 | 0 | 0 | +2 | +2 | −2 | +4 |
| **Price** | 7 | +14 | +7 | +14 | +14 | 0 | +7 |
| **Manufacturability** | 19 | +19 | +38 | 0 | −38 | −38 | +57 |
| **Durability** | 12 | −12 | +36 | −12 | +24 | −12 | 0 |
| **Adaptability** | 19 | +19 | 0 | −19 | +19 | −19 | +38 |
| **Total** | 100 | +122 | +71 | −8 | +35 | −126 | **+195** |

**Weight (%) × Ranking = Total**

# IV. Engineering Analysis and Design

This paper analyzes the most relevant parts of ORCA, focusing on its main structural component. The analysis was completed for each subcomponent, including the chain and the gears.

## A. Concept of Operation

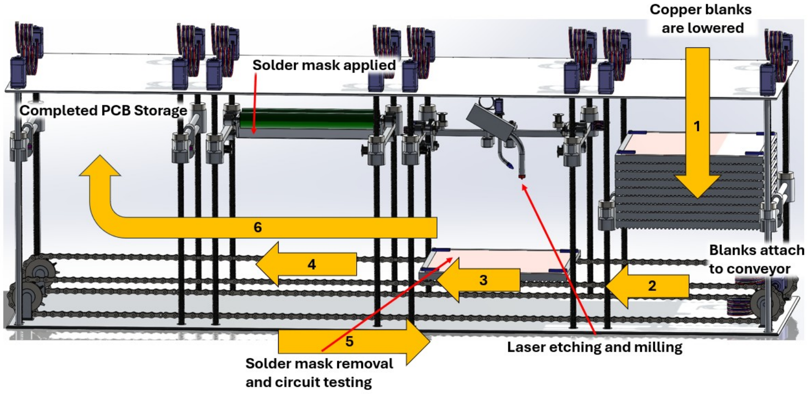


**Fig. 8 Concept of operations for the selected conceptual design.**

ORCA operates autonomously within the Arkysis Bosuns Locker, reducing the need for astronaut involvement in PCB manufacturing. When activated, the Dispenser and Storage mechanisms release a single copper blank onto the conveyor system, as depicted in Figure 8. Pre-installed retainer clips secure the boards within the PCB trays during machining and transportation throughout the ORCA system. The first stop on the conveyor is the laser-etching and milling station, where a circuit design is engraved onto the board. Following this, the board proceeds to the solder masking station, where a conductive film is applied to the top surface to facilitate electrical connections across the board.

Subsequently, the board returns to the previous station to remove excess mask material and undergoes an autonomous electrical conductivity test. This test verifies whether a connection is established between the conductive film and the board before it can be utilized for mission requirements. Once the conductivity test is complete, the finished board is transferred to the final storage unit, where it awaits the completion of nine additional boards, bringing the total stack to ten. Throughout the ORCA system, various visual and sensor equipment (not shown in the design) is strategically positioned to relay information back to astronauts, ensuring the system operates autonomously without requiring in-person checkups.

## B. Frame

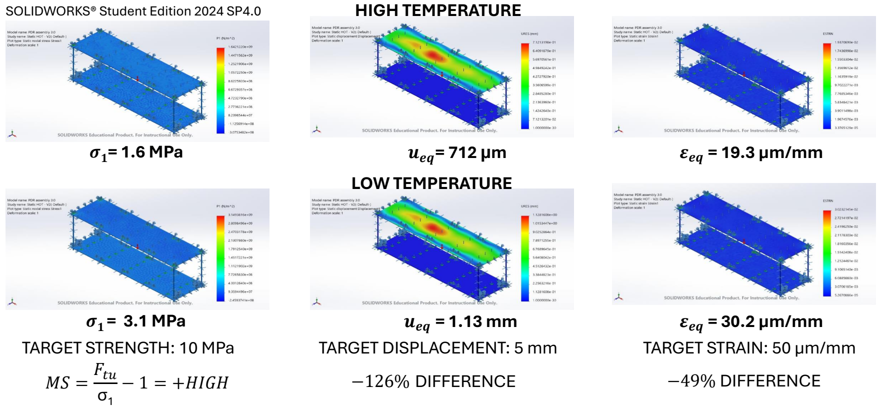
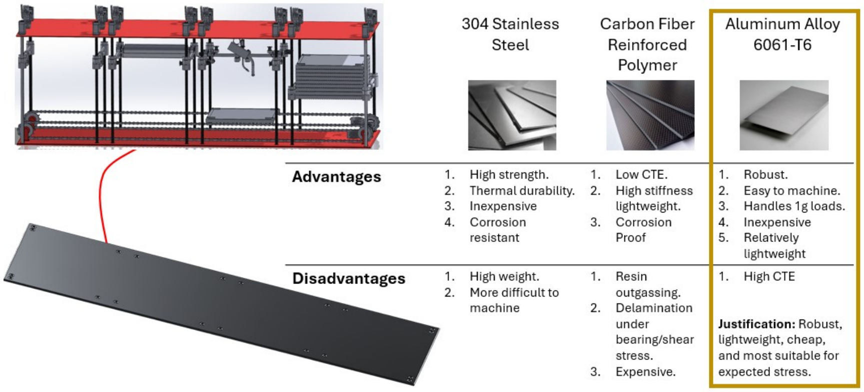


**Fig. 9 Finite element analysis of the frame assembly.**

The frame serves as the backbone of ORCA, designed to withstand deformation from thermal variations and manufacturing loads. It encompasses all key systems, including the dispenser and storage system, the laser-etching and milling system, the solder masking system, the conveyor system, and the debris management system. The engineering analysis was conducted using the worst-case scenario for a low-orbit environment, accounting for two thermal extremes: full shadow and direct sunlight, in order to simulate varying temperatures. Furthermore, the analysis used Earth's gravity as the baseline, since replicating the gravitational conditions of space is challenging without establishing a proper low-orbit vacuum environment. Finite element analysis was performed in SolidWorks 2024 with static thermal inputs, and the results are illustrated in Figure 9. The findings are categorized into three areas: the maximum principal stress to identify potential breakpoints, displacement constraints, and strain requirements. Overall, the results indicate that the frame maintains its structural integrity under thermal conditions. After confirming that the engineering analysis met the structural integrity criteria, we conducted trade studies on the frame material, as shown in Figure 10. The evaluation of these materials considered factors such as load capacity, cost, machinability, and durability. Ultimately, AL 6061-T6 emerged as the optimal choice due to its robustness, low weight, affordability, and ability to withstand anticipated stresses.



| | 304 Stainless Steel | Carbon Fiber Reinforced Polymer | Aluminum Alloy 6061-T6 |
|---|---|---|---|
| **Advantages** | 1. High strength.<br>2. Thermal durability.<br>3. Inexpensive<br>4. Corrosion resistant | 1. Low CTE.<br>2. High stiffness lightweight.<br>3. Corrosion Proof | 1. Robust.<br>2. Easy to machine.<br>3. Handles 1g loads.<br>4. Inexpensive<br>5. Relatively lightweight |
| **Disadvantages** | 1. High weight.<br>2. More difficult to machine | 1. Resin outgassing.<br>2. Delamination under bearing/shear stress.<br>3. Expensive. | 1. High CTE<br>**Justification:** Robust, lightweight, cheap, and most suitable for expected stress. |

**Fig. 10 Trade study for frame material**

## C. PCB Tray

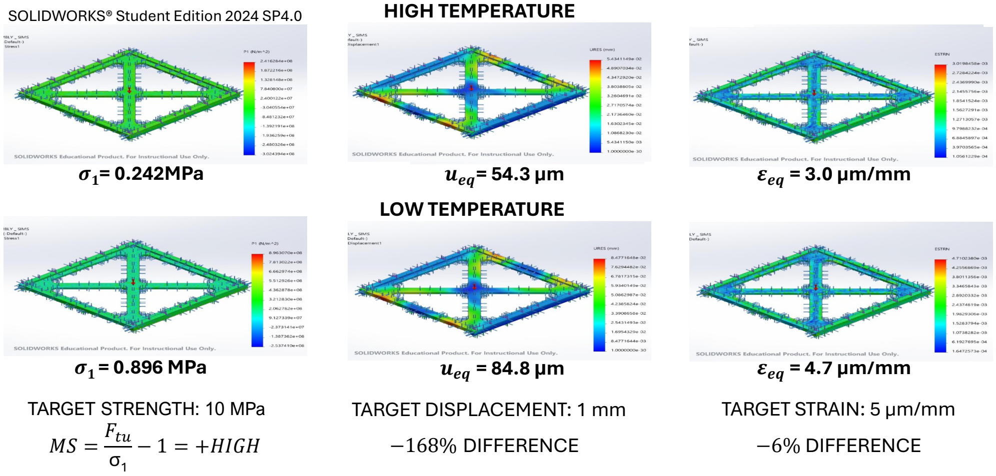
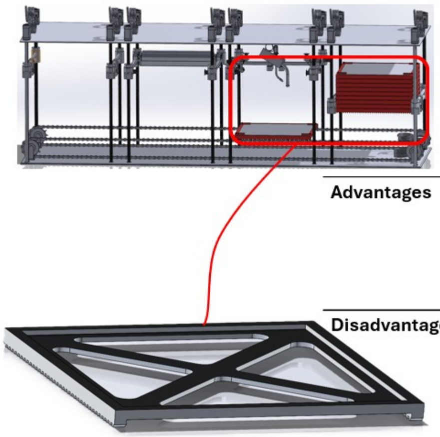


**Fig. 11 Finite element analysis of the PCB Tray assembly.**

The trays are designed to securely hold blanks during transportation and machining between stations within the ORCA system. Each tray is equipped with retainer clips that stabilize the PCB throughout manufacturing, preventing unnecessary movement. Beneath each tray lies a gear rack, which, in conjunction with the conveyor system's chains, facilitates movement during manufacturing. The analysis utilizes assumptions from the frame, with the additional consideration that loading from the other trays is transferred to the bottom tray. Boundary conditions are defined at the contact points established by the retainer clips and the center of the tray. The results presented in Figure 11 assess the first principal stress, displacement, and strain. It is determined that any additional loading will not compromise the tray's reliability, while the observed displacement and strain indicate minimal structural deformation at these extreme temperatures. Figure 12 presents trade studies comparing AL 6061-T6, carbon fiber-reinforced polymer, and anodized honeycomb. The decision to select AL 6061-T6 is driven by its excellent manufacturability, high thermal conductivity, and reliable mechanical performance under vacuum, making it the most practical and durable material for PCB tray applications.



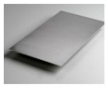
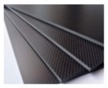
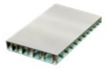
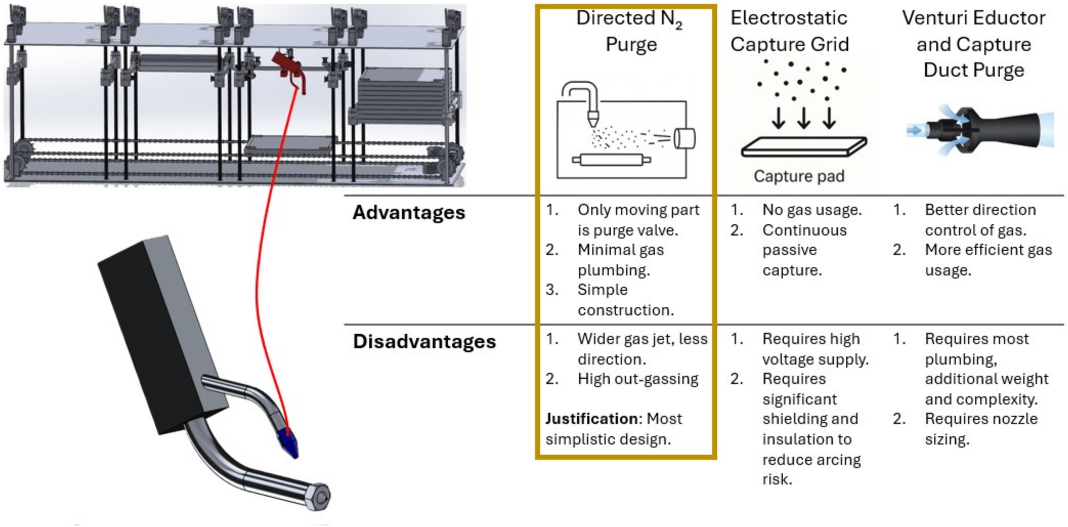
| | Aluminum Alloy 6061-T6  | Carbon Fiber Reinforced Polymer  | Anodized Aluminum Honeycomb  |
|---|---|---|---|
| **Advantages** | 1. Robust.<br>2. Easy to machine.<br>3. Handles 1g loads.<br>4. Low cost. | 1. Low CTE.<br>2. High stiffness lightweight.<br>3. Hybridized with Aluminum. | 1. High stiffness.<br>2. Low weight.<br>3. Thermal durability. |
| **Disadvantages** | 1. High CTE<br>2. Low CFRP<br>3. Need anodized coating<br>**Justification:**<br>Robustness along with ease of machinability. | 1. Resin outgassing.<br>2. Delamination under bearing/shear stress.<br>3. Expensive. | 1. Core crush under local overload.<br>2. Face-sheet delamination. |

**Fig. 12 Trade study for tray material**

### D. Laser-Etching and Expulsion Assembly

The laser-etching tool head produces electrical designs on PCBs via an automated system or user interface. Additionally, it employs a set of stepper motors, providing the tool head with three degrees of freedom. The debris management system effectively collects excess solder masking and hole-drilling particulates during the second and fourth stages of the production cycle. It stores them in a designated collection zone. The applied assumptions are consistent with those used for the frame, except that the boundary conditions are defined by the $x$-axis motor linked to the laser-etching and debris tool head, which is used to perform principal stress, displacement, and strain analyses. The trade studies were instrumental in identifying the most suitable inert-debris gas-expulsion system for removing and collecting particulates from the laser-etching station. Among the three options presented in Figure 13, the $N_2$ Purge emerged as the optimal choice due to its ease of implementation.



| | Directed $N_2$ Purge | Electrostatic Capture Grid | Venturi Eductor and Capture Duct Purge |
|---|---|---|---|
| **Advantages** | 1. Only moving part is purge valve.<br>2. Minimal gas plumbing.<br>3. Simple construction. | 1. No gas usage.<br>2. Continuous passive capture. | 1. Better direction control of gas.<br>2. More efficient gas usage. |
| **Disadvantages** | 1. Wider gas jet, less direction.<br>2. High out-gassing<br>**Justification**: Most simplistic design. | 1. Requires high voltage supply.<br>2. Requires significant shielding and insulation to reduce arcing risk. | 1. Requires most plumbing, additional weight and complexity.<br>2. Requires nozzle sizing. |

**Fig. 13 Trade study for debris expulsion attachment**

### E. Power screw

The power screw facilitates vertical movement of trays and gantries, enabling ascent and descent between machining stations while maintaining vertical alignment under vacuum. This motion is characterized by precision and linearity, thanks to the small stepper motors, which enable synchronized actuation and consistency throughout the production cycle. In this analysis, we focused on the 1/2-10 ACME screw type, which is a single-start design. The findings include the torque required to raise and lower the power screws, as well as their overall mechanical efficiency. The required torque for lifting and lowering the load is as follows:

$$\begin{aligned} T_{\text{raise}} &= \left(\frac{F\,d_{\text{m}}}{2}\right)\tan(\phi+\lambda) = \left(\frac{(1.62\text{ N})\,(0.01054\text{m})}{2}\right)\tan(8.80^\circ + 4.39^\circ) = 0.00200\text{ N-m} \\ T_{\text{lower}} &= \left(\frac{F\,d_{\text{m}}}{2}\right)\tan(\phi-\lambda) = \left(\frac{(1.62\text{ N})\,(0.01054\text{m})}{2}\right)\tan(8.80^\circ - 4.39^\circ) = 0.00066\text{ N-m} \end{aligned} \tag{1}$$

The motion is self-locking and load-bearing because the friction angle of the power screw exceeds its helix angle, ensuring stable vertical positioning. The mechanical efficiency of the power screw is:

$$\eta = \frac{\tan(\lambda)}{\tan(\phi+\lambda)} = \frac{\tan(4.39^\circ)}{\tan((8.80^\circ + 4.39^\circ)} = 0.33 \tag{2}$$

This indicates that the power screw operates at 33% efficiency, meaning that approximately one-third of the generated torque is converted into linear motion during both raising and lowering operations.

# V. Leading to Preliminary Design Review

The following sections outline the comprehensive system architecture and its subsystems. This assessment aims to ensure that the original design meets all requirements for the system, its subsystems, and its interfaces. The review will culminate in the Preliminary Design Review (PDR), giving stakeholders insight into the trade-offs made during the initial design phase. This process is vital for identifying and addressing potential issues before they develop into more costly solutions, thereby mitigating risk.

## A. Explaining the Design

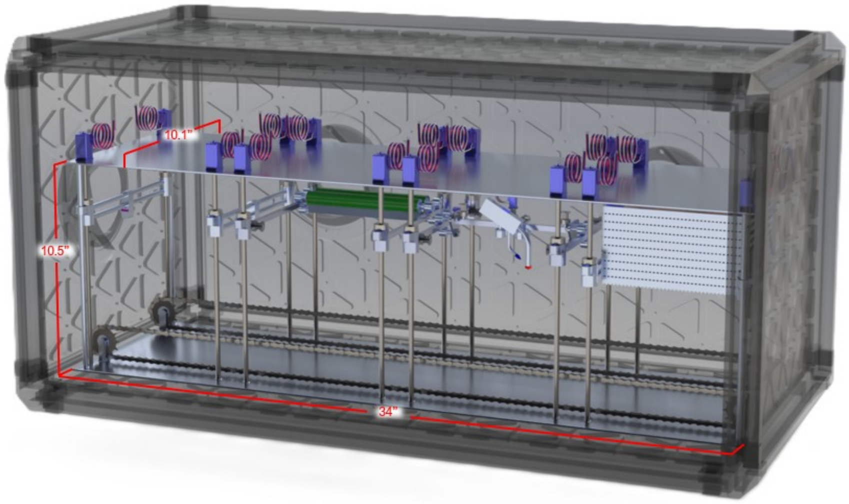
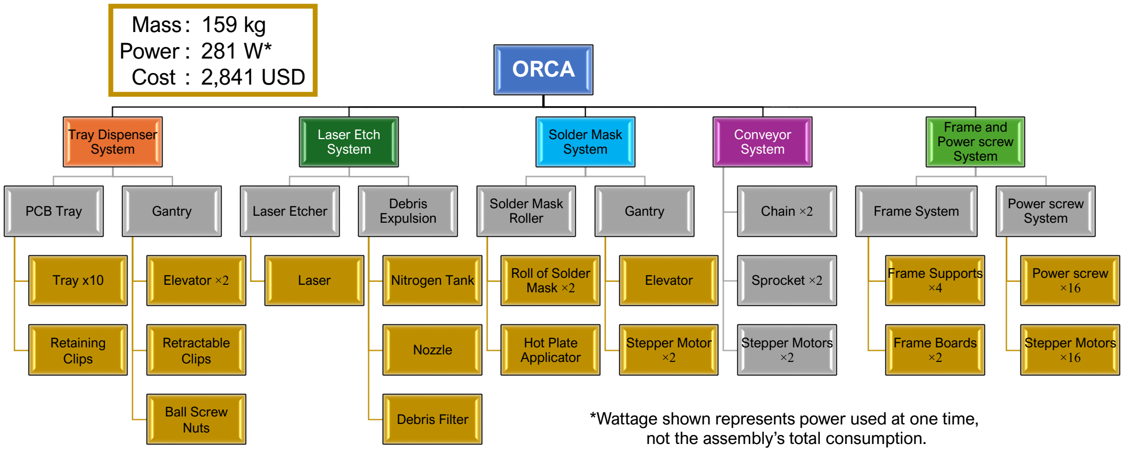


**Fig. 14 Final Design fitting inside the Arkysis Bosuns Locker**

Figure 14 shows that the Conceptual Design of In-Space Orbital Reliable Printed Circuit Boards (ORCA) aligns with the specifications of the Arkysis Bosuns Locker. Dual storage assemblies are used to store blank and completed PCBs. The dispenser system retrieves the blank PCBs and delivers them to the conveyor for processing. This system ensures a continuous workflow and minimizes human interaction during PCB loading and storage. The laser etcher applies standard or custom circuit patterns to blank PCBs and is equipped with a debris-removal attachment on the tool head to remove particulates generated during milling. This closed-loop vacuum system prevents contamination of critical components and maintains their integrity in a microgravity environment. The solder mask applicator deposits a protective conductive film on the etched PCBs. An automated roller and curing system guarantees uniform coating thickness. Integrated into the gantry, inspection cameras provide in situ verification of mask uniformity, further reducing the need for human intervention. These cameras are part of the intended final design but are excluded from the mass, power, and cost analysis.

## B. Mass, Power, and Cost Analysis

To evaluate the mass, power, and cost of the ORCA system, the team divided the assembly into five primary subsystem categories, each represented by a color-coded box in Figure 15. The tray dispenser system is orange, the laser etching system is dark green, the solder mask system is teal, the conveyor system is magenta, and the frame and power screw system is light green. These five categories represent the essential stages of the PCB fabrication process that ORCA will demonstrate, allowing for consistent analysis of the supporting hardware. Grouping the assembly by tasks helps us understand how mass, power, and cost are distributed across ORCA's workflow. This category-division approach simplifies the evaluation of the design with respect to Bosuns Locker's power and volume constraints, while avoiding the need to itemize every individual part and representing the interactions among critical elements of the ORCA system.



*Wattage shown represents power used at one time, not the assembly's total consumption.

**Fig. 15 Mass, Power, and Cost Analysis flow chart**

Figure 16 summarizes the distributions of mass, power, and cost. The assessment shows that the frame and power screw system is the heaviest among all subsystems, followed closely by the laser etching system. This heaviness is primarily due to these subsystems providing mechanical rigidity, load-bearing capabilities, and high-precision laser alignment for all machining operations. A closer examination of their respective subsystems reveals that they also contribute significantly to the overall weight; for instance, the sturdy aluminum frame and the heavy laser with precision capabilities outweigh smaller mechanisms such as conveyor chains, sprockets, or elevator arms. The mass of the ORCA system is well within the required limit for the Arkysis Bosuns Locker, accounting for 159 kg of the 400 kg maximum. The remaining mass capacity provides flexibility to address potential risks or necessary enhancements, such as shielding, thermal components, and other system aspects, for future testing and validation.

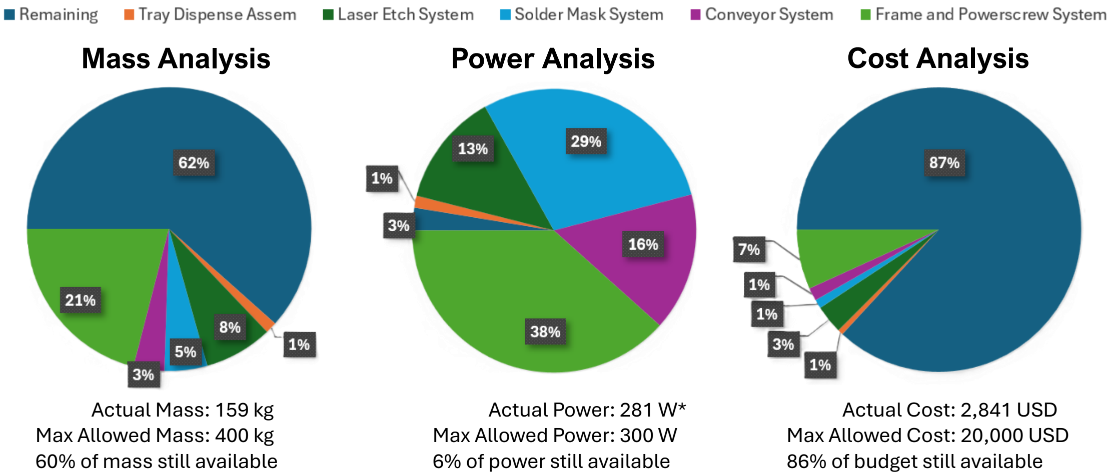
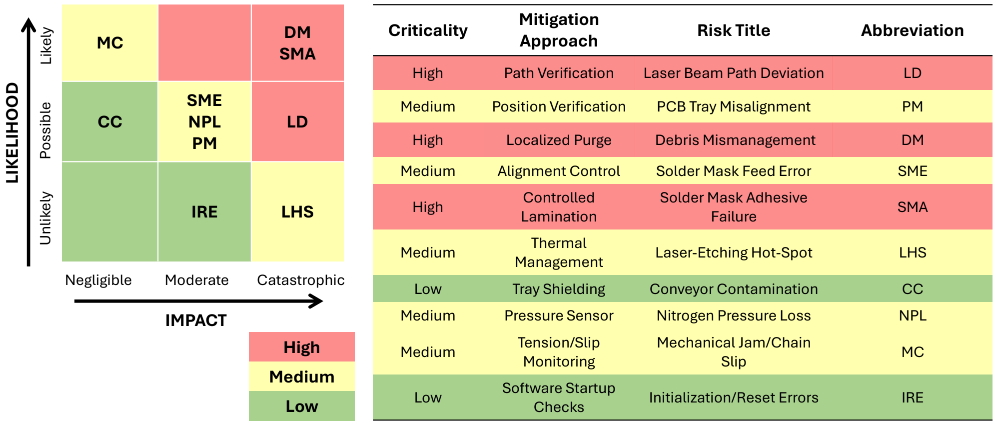


**Fig. 16 Mass, Power, and Cost Analysis Pie Charts Breakdown**

In terms of power distribution, the frame and power systems are the dominant subsystems, followed closely by the solder mask system. The need for numerous stepper motors in the frame and power screw systems arises from axial translation at each station, which adjusts the PCBs vertically. The laser etching system also features stepper motors, though fewer than in previous systems, along with a hot plate applicator for controlling the laser. The ORCA system's total power consumption is within the acceptable range for the Arkysis Bosuns Locker, drawing 281 W, which is below the 300 W limit. However, limited power availability limits opportunities to advance electronic capabilities, even though mass and cost budgets offer considerable room for growth.

Regarding cost distribution, the frame and power screw system is the most expensive subsystem, followed by the laser etching system. This is because the frame and power screw system serves as the ORCA system's structural backbone, providing vital structural integrity, vibration resistance, and rigidity. The laser etching system requires acquiring an entire laser apparatus, which must be dismantled to retrieve the laser head. Given the remaining prototype budget and the decision criteria, the ORCA system allocates less than 15% of the maximum budget. Consequently, this prototype has the potential to enhance the design solely by utilizing the excess budget already allocated for the necessary subsystem components.

### C. Risk Assessment



| Criticality | Mitigation Approach | Risk Title | Abbreviation |
|---|---|---|---|
| High | Path Verification | Laser Beam Path Deviation | LD |
| Medium | Position Verification | PCB Tray Misalignment | PM |
| High | Localized Purge | Debris Mismanagement | DM |
| Medium | Alignment Control | Solder Mask Feed Error | SME |
| High | Controlled Lamination | Solder Mask Adhesive Failure | SMA |
| Medium | Thermal Management | Laser-Etching Hot-Spot | LHS |
| Low | Tray Shielding | Conveyor Contamination | CC |
| Medium | Pressure Sensor | Nitrogen Pressure Loss | NPL |
| Medium | Tension/Slip Monitoring | Mechanical Jam/Chain Slip | MC |
| Low | Software Startup Checks | Initialization/Reset Errors | IRE |

**Fig. 17 Risk Assessment for Design Concept.**

The team has identified several risks that could threaten the reliability and performance of the ORCA manufacturing device within the Bosuns Locker. Figure 17 illustrates these risks using a typical color-coded criticality scale and outlines the corresponding mitigation strategies for each identified risk. These risks were assessed based on their potential impact on PCB quality, subsystem functionality, and the overall workflow, resulting in a tailored mitigation plan for each failure mode. The risks deemed most critical to the ORCA device include debris management, solder mask adhesion defects, and deviations in the laser beam path.

Debris mismanagement poses the greatest risk to the system. Laser etching and drilling generate particulate debris that can float freely in microgravity conditions and settle on sensitive surfaces. This debris may obstruct sensors, interfere with solder mask adhesion, or accumulate and impede component movement. To address debris removal, the team utilized the unpressurized environment of the Bosuns Locker. ORCA reduces debris risk by employing a localized nitrogen jet at the tool head and a small capture shroud that directs debris particles toward a designated exhaust port in the Bosuns Locker. This approach confines debris to the etching module, minimizing the risk of contaminating other system components.

Solder mask adhesion failure is another high-criticality risk because of its potential impact on board quality and functionality. Incomplete curing, uneven application pressure, uneven lamination, or insufficient bonding can lead to electrical discontinuities or expose conductive copper. To mitigate this risk, ORCA uses tightly regulated roller pressure, spool feed speed, and hot-plate applicator temperatures, and verifies proper solder mask application with onboard inspection cameras in the solder mask module.

Laser beam path deviation is also classified as a high-criticality risk because it can cause structural damage to the ORCA device or result in improper etching of the PCB blank. The mitigation strategy includes beam stops to protect the frame, reflective shielding on the PCB tray, encoder-controlled gantry positioning, and software that disables the laser if the gantry position deviates from the programmed trajectory. Medium-criticality risks pose hazards to mechanical operation, process reliability, and consistency. Dry-film solder mask feed errors, such as misalignment, tension irregularities, and wrinkling, are addressed by ORCA using film roll alignment guides, controlled roller tension and feed speed, and verification via the onboard inspection camera.

Mechanical jamming or chain slippage in the conveyor system can cause drive motor burnout or misalignment of the PCB tray relative to other workstations, disrupting the processing workflow. This risk is mitigated by ensuring appropriate chain tension, employing encoder-based chain-stall detection, implementing software-based motor overload safeguards, and providing a reset function that returns the PCB tray to its starting position upon detection of conveyor misalignment.

Misalignment of the PCB tray on the conveyor surface is another medium-criticality risk, as it may result in incorrect features at either the laser or solder mask station. ORCA mitigates this risk by using mechanical locating features on both the conveyor surface and the PCB tray to ensure proper seating, and by using inspection cameras at the solder mask station to verify positioning prior to critical processing steps.

Additional medium-criticality risks include nitrogen supply pressure loss and hot-spot formation during laser etching. In the vacuum conditions of the Bosuns Locker, convection is absent, leading to localized heating that can deform the substrate or cause copper delamination. ORCA addresses this issue by strategically planning the toolpath to minimize heat buildup, using pulse-width modulation, and limiting the laser duty cycle. A decrease in nitrogen supply pressure could impair ORCA's ability to manage and eliminate debris. A pressure sensor and a software-controlled minimum-flow threshold are in place to prevent etching when the nitrogen supply is insufficient to maintain effective debris control.

Low-criticality risks include conveyor contamination and system initialization/reset errors. The current design of the ORCA device lacks dedicated debris shields for the conveyor; however, the PCB tray itself blocks the most direct path for particulates to enter the chain and sprocket assembly, and the directed nitrogen purge system helps mitigate this risk. Initialization and reset errors are minimized by implementing multiple software checks for position, speed, and alignment, ensuring that the system operates correctly during manufacturing.

These mitigation strategies enable ORCA to operate reliably under the conditions and constraints of the Arkisys Bosuns Locker. This risk analysis was incorporated into the design process, enabling future improvements and refinements as more detailed testing and research are conducted.

## D. NASA Technology Readiness Levels

The assessment of technology readiness levels (TRL) follows NASA's established definitions, illustrating the maturity of the overall ORCA system and its key subsystems. In this framework, TRL-1 indicates that the technology is in the research phase, whereas TRL-9 indicates that the technology has been validated through a successful mission. Figure 18 depicts the various TRLs for the proposed conceptual design.

The ORCA system is classified at TRL-4, indicating that it has been validated in a laboratory setting using limited publicly available information. The Solder Mask Applicator and the Debris Management and Nozzle System are both

**OVERALL DESIGN:**
ORCA Device | L4 |
**SUBSYSTEMS:**
PCB Tray and Retaining Clips | L4|
Chain and Sprocket Assembly | L5 |
Stepper Motors and Drivers | L5 |
Gantry Positioning System | L4 |
Power Screw for Gantry Actuation | L5 |
Aluminum Frame | L6 |
Solder Mask Applicator | L3 |
Laser Etcher Tool Head | L4 |
PCB Storage and Retrieval Dispenser | L4|
Debris Management and Nozzle System | L3 |
Motion Control and Sequencing Logic | L4 |

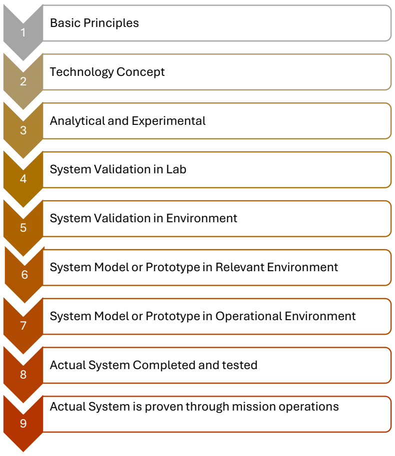


**Fig. 18 NASA Technology Readiness Level**

rated at TRL-3, indicating that analytical and experimental data support their performance in microgravity. Subsidiary systems classified at TRL-4 include the PCB tray and retaining clips, the gantry positioning system, the laser etch tool head, the PCB storage and dispenser, and the motion control and sequencing logic; all have undergone laboratory validation. Additionally, the chain and sprocket assembly, along with the power screw, has been tested in a controlled lab environment. In contrast, the aluminum frame is classified at TRL-6, indicating that it has been modeled and simulated in a relevant environment—specifically, microgravity.

### E. Key Design Impacts (Innovation)

Manufacturing PCBs in space presents exciting new opportunities for exploration and on-demand production. This innovative system significantly enhances PCB production capabilities, particularly given the limited experimental testing currently conducted in space. The process entails creating new PCBs from blank boards or recycled materials, such as repurposed old circuit boards. Techniques involved include laser etching, milling, solder masking, and circuit validation. This advancement enables an autonomous production supply chain, reducing reliance on Earth for PCB resupply during space missions. Moreover, the system's autonomy allows astronauts to focus on other essential tasks while the uniquely designed printed circuit boards are fabricated in the background.

Additionally, installing a closed-loop debris-expulsion unit around the toolhead station effectively collects particulates, preventing contamination within the movement system. This ensures reliable PCB production at a faster pace than traditional manufacturing and Earth-to-space shipping processes, which often entail high costs and long timelines. The capability to repair, reconfigure, and fabricate PCBs autonomously aboard a spacecraft closely aligns with ISAM and NASA's objectives. This approach promotes a sustainable, resource-efficient, and resilient PCB manufacturing assembly line in space.

### F. Design Technical Gap Assessment

To achieve the necessary precision and accuracy in circuitry, advances in small-laser etching technology are crucial, particularly for vacuum-based processes. Further research into debris-expulsion or mitigation technologies is vital to prevent issues associated with these factors from impacting ORCA's current setup. Additionally, it will be important to develop specialized laser-etchable PCB blanks to sidestep complications arising from existing PCB technologies, such as excessive off-gassing or warping.

## VI. Final Remarks

### A. Conclusions

ORCA not only met the goals and requirements of the COSMIC Capstone Challenge but also achieved excellent results in mass, power, and cost, remaining within the maximum limits. The team undertook a comprehensive engineering and simulation effort across multiple subsystems, considering a wide range of criteria and potential challenges. Collaboration with an industry mentor enabled the team to adapt ORCA by incorporating cutting-edge technologies. This included developing conceptual designs into current applications tailored to ORCA's needs, such as an inert-gas debris management system, a zero-gravity solder-mask film applicator, and a PCB storage and conveyor system.

In addition, ORCA demonstrated the viability of its concept through simulations and analyses of component stress, strain, and displacement under extreme environmental conditions. The project adhered to the specified Count of Commercial Off-The-Shelf (COTS) components, making the subsequent development of a physical prototype feasible and significantly less complex. If the physical prototype is successfully developed, it could reduce reliance on Earth-based resupply missions for custom components, paving the way for in-space manufacturing. This advancement would extend mission objectives and provide greater benefits for crew members. Overall, if this design progresses from the conceptual stage to prototyping and testing, it could revolutionize the aerospace industry and advance PCB research for space applications.

### B. Recommendations

The Deep Interstellar Solutions team has several design recommendations for developing a prototype of this technology.

1. First, it is recommended to conduct thermal simulations using SolidWorks or other suitable FEA software under transient conditions. All previous simulation runs were performed under steady-state conditions for both temperature extremes. Analyzing transient conditions is essential to demonstrate the impact of rapid heating and cooling cycles in an orbital environment. This analysis will elucidate how temperature fluctuations affect the structural stability of ORCA and the integrity of its solder joints.
2. Second, there is a need to evaluate the performance of components in microgravity, specifically focusing on friction and torque behavior in a vacuum. The initial approach assumed that each component operates optimally in microgravity. Therefore, it is crucial to investigate how friction and torque influence the performance of power screws, stepper motors, and conveyor belts in a vacuum setting.
3. The team has discussed fail-safes, but we have yet to conduct a thorough evaluation. One plan is to implement redundant sensors and real-time fault detection to validate and safeguard the PCBs. This approach will alert astronauts as soon as an issue arises within the Arkysis Bosuns Locker.
4. Another topic of discussion has been circuit testing. Due to time constraints, we have made limited progress in this area. Moving forward, it would be beneficial to develop a probing system to test conductivity and contact points, thereby assessing the reliability of PCB manufacturing.
5. Additionally, the laser tool head component will require further testing to evaluate its capabilities. We should conduct additional analysis using models that simulate vacuum conditions to accurately assess performance in orbital environments.

### C. Lessons Learned

The team effectively broke down issues into smaller, manageable components through collaborative decision-making. This approach not only fostered teamwork but also enhanced conflict resolution skills. By proactively adjusting the schedule, the team successfully achieved the project milestones. The organizational strategies employed contributed to the efficient allocation of both resources and time. Additionally, the team gained valuable experience in industry and government practices for storing and managing digital documents to ensure compliance with security policies. Furthermore, the team expanded its expertise in space manufacturing technology and engineering, including proficiency in CAD animations, finite element analysis (FEA), and heat transfer analysis. Ultimately, the team also cultivated both soft and technical skills, including creating PowerPoint presentations, writing journal papers, and honing public speaking skills. This experience culminated in a first-place finish at the 2025 KSU Senior Design Expo.

## Acknowledgments

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## References

[1] National Science & Technology Council, "In-Space Servicing, Assembly, and Manufacturing National Strategy," Tech. rep., In-Space Servicing, Assembly, and Manufacturing Interagency Working Group, Executive Office of the President of the United States, 2022. URL `https://www.whitehouse.gov/wp-content/uploads/2022/04/04-2022-ISAM-National-Strategy-Final.pdf`.

[2] Dremann, K., Hassan, M., Davis, I., Orosa, A. V., Ninan, N., Mahajan, A., Gao, X., and Farhad, S., "A Review of Advancements in Inspection, Manufacturing and Repair, and Robots for On-Orbit Servicing, Assembly, and Manufacturing (OSAM) of Spacecraft," *Aerospace*, Vol. 12, No. 9, 2025. https://doi.org/10.3390/aerospace12090819.

[3] Arney, D., Mulvaney, J., and Williams, C., "In-Space Servicing, Assembly, and Manufacturing (ISAM) State of Play: 2025 Edition," Tech. rep., NASA Langley Research Center, 2025. URL https://ntrs.nasa.gov/api/citations/20250008988/downloads/NASA_ISAM_State_of_Play_2025_Edition.pdf?attachment=true.

[4] Prater, T., Werkheiser, N., Ledbetter, F., and Morgan, K., "In-Space Manufacturing at NASA Marshall Space Flight Center: A Portfolio of Fabrication and Recycling Technology Development for the International Space Station," *AIAA SPACE Forum*, AIAA, Orlando, FL, 2018. URL https://ntrs.nasa.gov/api/citations/20180006401/downloads/20180006401.pdf.

[5] Cauwe, M., "High-Density PCB Technology Assessment for Space Applications," *IPC APEX EXPO Technical Conference 2020*, San Diego, CA, 2020.

[6] Prince, J., "NASA Engineering and Safety Center (NESC) 2021 Technical Update," Tech. rep., NASA Langley Research Center, NASA/TM-20210024654, 2021. URL https://ntrs.nasa.gov/citations/20210024654.

[7] Courtright, Z. S., Jones, J. M., Blanchard, A. J., Bonebrake, J. M., Bryan, T. C., Evans, W. C., Fox, A. T., Francis, C. J., Hill, C. W., Jaynes, E. K., Kimbrel, B. A., Ledbetter, F. E., Lu, I. K., O'Connor, A., Peeples, S. R., Protz, C. S., Roberts, C. E., Rupp, B. L., Shake, P. D., Sowards, J. W., Subedi, R., Koehne, J. E., and Seol, M., "In-Space Manufacturing Portfolio Plan," Tech. rep., NASA Marshall Space Flight Center, NASA/TM-20250004020, 2025. URL https://ntrs.nasa.gov/api/citations/20250004020/downloads/ISM%20Portfolio%20Plan%20Baseline%20for%20Public%20Release%20R1c.pdf.

[8] Hanson, I., "Research Campaign: The Sciences of Space Manufacturing," Tech. rep., NASA Marshall Space Flight Center, July 2021. URL https://ntrs.nasa.gov/citations/20210025971.

[9] Heltzel, S., Cauwe, M., Bennett, J., and Rohr, T., "Advanced PCB Technologies for Space And Their Assessment Using Up-To-Date Standards," *CEAS Space Journal*, Vol. 15, No. 1, 2023. https://doi.org/10.1007/s12567-021-00404-1.

[10] Trujillo, A. E., Tu, A., Rome, J., Goyal, V., and Strizzi, J., "The Economic Case for an Orbital Satellite Factory," *AIAA ASCEND 2023*, AIAA. No. AIAA-2023-4676, Las Vegas, Nevada, 2023. https://doi.org/10.2514/6.2023-4676.

[11] Malshe, H., Bapat, S., Vickers, J., and Malshe, A. P., "Factories-in-space for servicing, assembly, & manufacturing," *Manufacturing Letters*, Vol. 38, 2023, pp. 24–28. https://doi.org/10.1016/j.mfglet.2023.08.142.

[12] Skomorohov, R., Welch, C., and Hein, A. M., "In-orbit Spacecraft Manufacturing: Near-Term Business Cases Individual Project Report," Tech. rep., International Space University Strasbourg Central Campus, Illkirch-Graffenstaden, France, 2016. URL https://api.semanticscholar.org/CorpusID:86742240.

[13] Rome, J., Espalin, D., Gupta, S., and Schaal, C., "Conceptual Development Design Challenge of On-Orbit Autonomous Manufacturing Payloads," *Defense Manufacturing Conference 2023*, Nashville, Tennessee, 2023.

[14] Cavaciuti, A. J., Heying, J. H., and Davis, J., "In-Space Servicing, Assembly, and Manufacturing for the New Space Economy," Tech. rep., Aerospace Center for Space Policy and Strategy, July 2022. URL https://csps.aerospace.org/sites/default/files/2022-07/Cavaciuti-Davis-Heying_ISAM_20220715.pdf.

[15] Arney, D., Sutherland, R., Mulvaney, J., Steinkoenig, D., Stockdale, C., and Farley, M., "On-orbit Servicing, Assembly, and Manufacturing (ISAM) State of Play," Tech. rep., NASA Langley Research Center, 2022. URL https://ntrs.nasa.gov/api/citations/20220010995/downloads/isam_state_of_play_final_2022.pdf.

[16] Agwu, U., Atre, R., Heying, J., and Rome, J., "2025-26 COSMIC Capstone Challenge – Information Packet – Fall Update," Tech. rep., COSMIC – Consortium for Space Mobility and ISAM Capabilities, 2025. URL https://cosmicspace.org/c3/.

[17] Salminen, A., and Vesterinen, T., "Laser processing of PCB," *ICALEO 2004: 23rd International Congress on Laser Materials Processing and Laser Microfabrication*, ASME, San Francisco, California, USA, 2004. https://doi.org/10.2351/1.5060329.

[18] Lim, W. Y. L., Jaafar, M., Marsilla, K. I. K., and Chinniah, K., "Recent Developments in Advanced Polymeric Materials for Solder Mask Application: Progress and Challenges," *Journal of Science Advanced Materials and Devices*, Vol. 8, No. 3, 2023. https://doi.org/10.1016/j.jsamd.2023.100567.

[19] Guler, K., and Petrisor, D. M., "A Pugh Matrix based product development model for increased small design team efficiency," *Cogent Engineering*, Vol. 8, No. 1, 2021. https://doi.org/10.1080/23311916.2021.1923383.