Manufacturing of Cold-welded Assemblies (MOCA)

Keven Duong[*], Kimo-Mark Hesse[†], Cordelia Kohuth[‡], Daniel Mount[§], Ela Ozatay[¶], and Manan Patel[‖]
Embry-Riddle Aeronautical University, Prescott, Arizona, 86301

Manufacturing of Cold-Welded Assemblies (MOCA) is a Senior Capstone project developed during the Fall 2025 semester at Embry-Riddle Aeronautical University's Prescott Campus. MOCA aims to design an Earth-based prototype capable of cold welding two aluminum members. Cold welding is a solid-state joining process in which two clean, oxide-free metal surfaces bond at the atomic level when subjected to sufficiently high pressure. To enable this manufacturing technique, the system removes the aluminum oxide layer from each member before applying a high clamping force at a designated point. The system operates in a vacuum to prevent re-oxidization of the surface. This document presents the whole engineering process MOCA underwent to create the cold welding system for the COSMIC C3 Challenge for track 1. The whole process includes trade studies, Concept of Operations, and the operational sequence to conduct the semi-autonomous cold welding process. The document outlines the three subsystems within MOCA and their respective requirements. MOCA also discusses the Controls Software Architecture and data handling and interface where MOCA's code enables the cold welding operation. This document then discusses other innovations that MOCA considered, and lessons learned including innovative ideas such as using a laser to clean the metallic members or to communicate between components, technological limitations, and challenges faced throughout the whole engineering process. Additionally, MOCA presents potential risks, outlines corresponding mitigation strategies and then re-assesses the initially determined risk levels.

---

[*] Student
[†] Student
[‡] Student
[§] Student
[¶] Student
[‖] Student

I. Introduction

As humans venture deeper into space, large, pressurized structures need to be constructed and repaired to contain the higher number of astronauts. Manufacturing Of Cold-Welded Assemblies (MOCA) offers a solution to meet construction demands for space exploration. MOCA is competing in the COSMIC Capstone Challenge (C3), track 1. COSMIC stands for Consortium for Space Mobility and In-Space Servicing, Assembly and Manufacturing (ISAM) Capabilities. Track 1 requests a payload design to be hosted in Arkysis' Bosuns Locker that demonstrates three or more operations for orbital manufacturing and assembly [1]. MOCA will provide the capability to build large structures in space using cold welding. The cold welding technique that MOCA will utilize joins two pieces of metal by preparing the surface of the materials and applying pressure to weld the metal members together. With the ability to cold weld joints, MOCA supports future space exploration.

MOCA will support future space exploration by providing benefits of building large structures in space, reducing launches, using cold welding in space, and reducing complications involving payload restrictions. The first major benefit of MOCA is the capability to build large structures in space. As humans continue to explore beyond Earth, large-scale structures need to be constructed or re-built to support human life. The second major benefit of MOCA is having fewer launches for future projects launched into space. With the use of MOCA, large structures will not need to be assembled on Earth and sent to space through multiple launches. The third major benefit of MOCA is conducting cold welding in space. The use of welded joints in space allows for structures to be pressurized to support human life and can provide welded components without the use of traditional welding fuels and filler materials. The fourth major benefit of MOCA is limiting complications involving payload restrictions within rockets. MOCA will only need to be supplied with additional material stock, which can be much simpler to fit within a specified payload size, creating less complications within payload restrictions. Overall, MOCA provides significant benefits for building and assembling large structures in space that will propel human exploration beyond Earth.

II. System Overview

To further abilities to construct large structures in space, MOCA demonstrates a joining method of two Aluminum 3003 members using cold welding. MOCA's finalized design can be seen in Fig. 1. MOCA performs cold welding through its Mechanical Subsystem, comprised of three mechanisms: the Cleaning Mechanism, the Alignment Mechanism, and the Pressure Mechanism. Each of the three mechanisms are labeled to show where in MOCA they are located. More detail on the structure and function of each mechanism is provided in II.C System Architecture Overview. In addition to the Mechanical Subsystem, MOCA has two other subsystems, the Electrical Subsystem and the Control Software Subsystem, which are responsible for making sure power is provided to all the subsystems, processing sensor feedback, and executing command sequences.

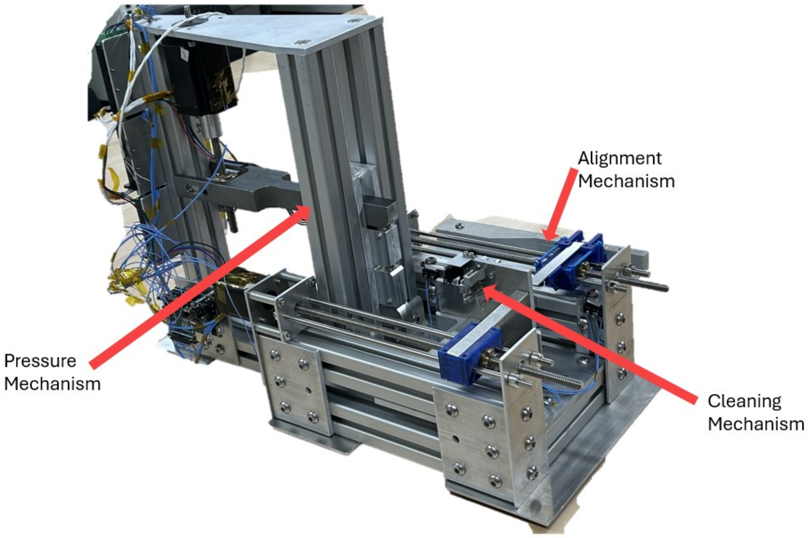

Fig. 1 Isometric View of MOCA

A. Concept of Operations

The Concept of Operations (ConOps) for MOCA, from launch to de-orbiting, is described visually in Fig. 2. Truss members will be prefabricated on Earth and launched into orbit alongside MOCA. MOCA will rendezvous with the materials, which will feed into MOCA. MOCA will then process the materials and begin construction of the truss structure. At the end of its life, MOCA will be deorbited and will burn up on re-entry.

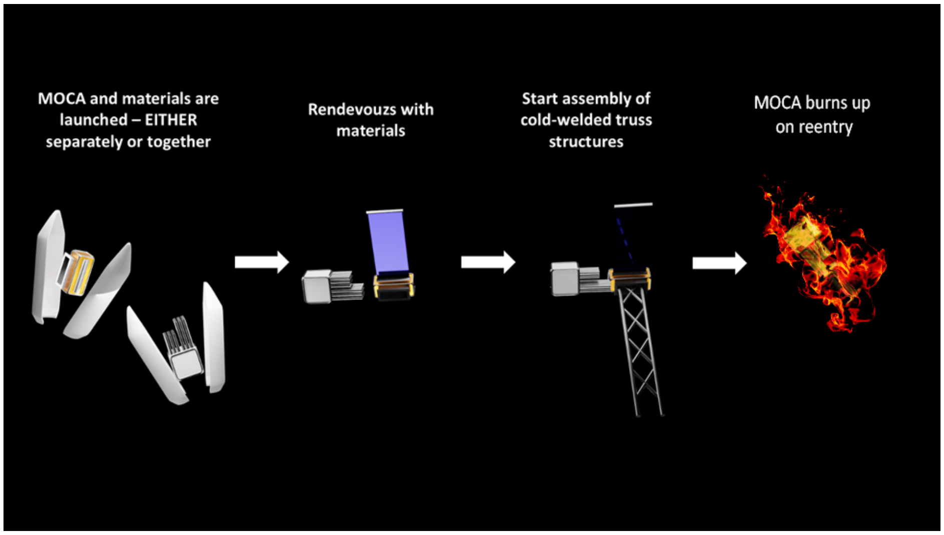

Fig. 2 Mission Overview

It is important to consider the overall mission structure when developing MOCA's design. The assembly of truss structures requires multiple discrete operations. To demonstrate how MOCA will perform its three discrete operations, the following ConOps is proposed. Figure 3 shows a generic overview of the cold welding operation at the core of MOCA.

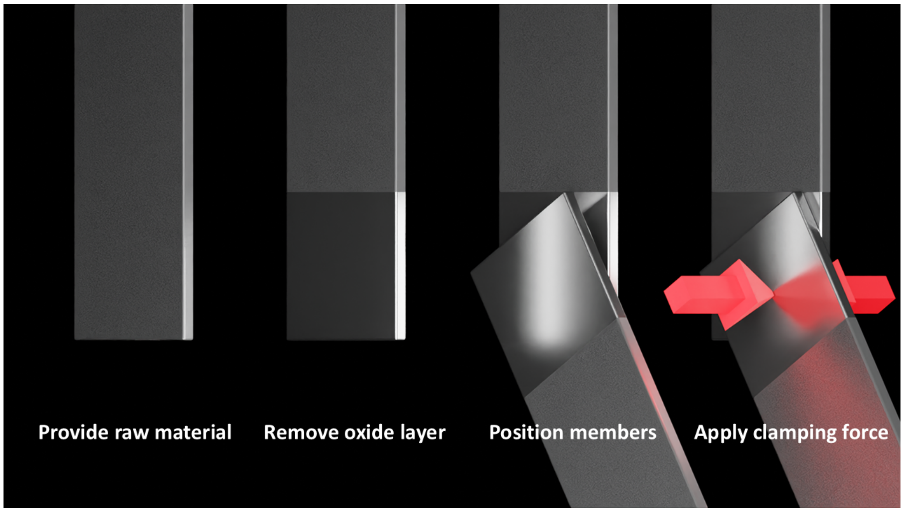

Fig. 3 Cold Welding Operation Overview

Members will be provided externally to MOCA to construct truss members, as shown in Fig. 3. MOCA will utilize a cleaning process to remove the oxide layer from the aluminum members. Removing the oxide layer allows for pure metal-to-metal contact, allowing easier bonding between metal atoms. The members will then be positioned into a desired orientation and clamped to start the cold welding process.

B. Operational Sequence

From the above ConOps, the complete operation of MOCA can be summarized in the following sequence:

1) Members are secured to the alignment carriages.
2) Members are translated into the Cleaning Mechanism.
3) Abrasive brushes remove the oxide layer from the weld region.
4) Nylon brushes remove residual debris.
5) Members are repositioned to form a lap joint.
6) Aligned members are translated into the Pressure Mechanism.
7) Force is applied to plastically deform the members.
8) A cold welded joint is formed.
9) The system moves out of the Pressure Mechanism and the cold welded assembly is removed.

The operational sequence provides the steps taken by each mechanism as well as how they interact as a complete system.

C. System Architecture Overview

From the operational sequence and ConOps, MOCA has several operations to complete which are divided into different subsystems. MOCA is comprised of three primary mechanisms which are supported by the Electrical and Control Software Subsystems: the Cleaning Mechanism, the Alignment Mechanism, and the Pressure Mechanism. These subsystems work together to form a cold welded joint. Figure 1 shows an isometric view of MOCA.

The Cleaning Mechanism is used to remove the oxide layer from the members, shown in Fig.4. The oxide layer is removed using abrasive wire brushes and then nylon brushes to remove the loose debris. This mechanism is crucial as it makes sure the members have the proper surface preparation to achieve a strong cold weld.

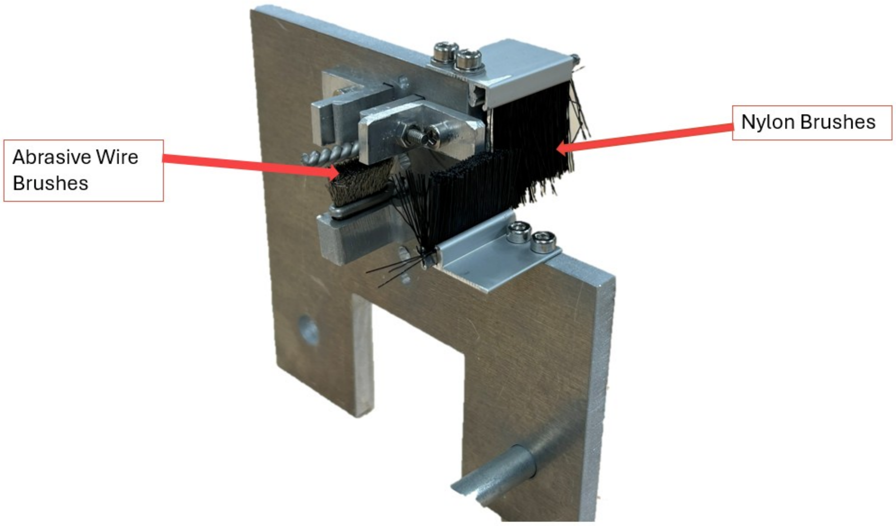

Fig. 4 Cleaning Mechanism

The Alignment Mechanism is responsible for moving the members through the cleaning mechanism, forming the lap joint overlap, and then moving the members to the pressure mechanism. The Alignment Mechanism is shown in Fig.5 with the Cleaning Mechanism.

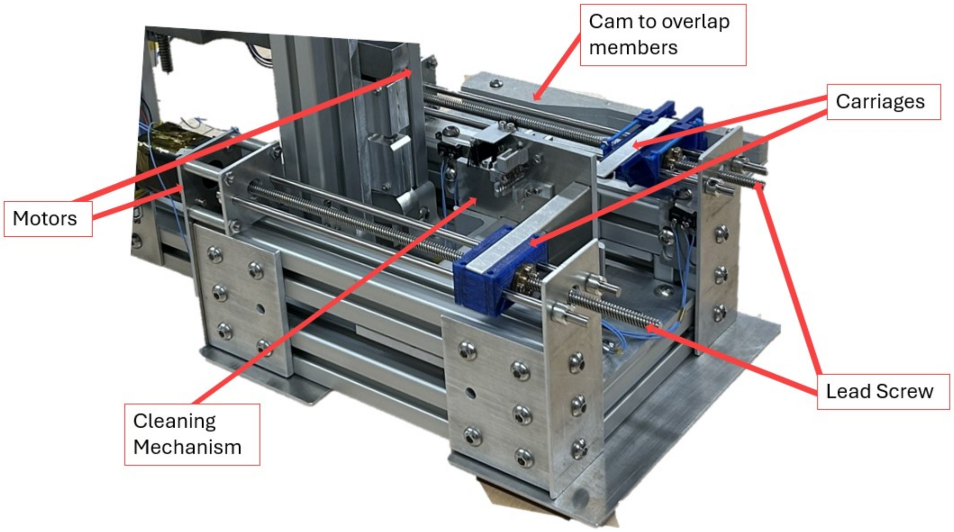

Fig. 5 Alignment Mechanism with Cleaning Mechanism

Two carriage assemblies are used, with one on the left side and one on the right. The left carriage assembly uses a lead screw and motor to translate the carriage along one axis. The right carriage incorporates two degrees of freedom by adding a cam mechanism to slide the member along a second axis.

The Pressure Mechanism applies the force needed to produce the necessary plastic deformation for a successful cold weld to occur. The overall Pressure Mechanism is shown in Fig. 6. The crimper is shown to the right of the Pressure Mechanism.

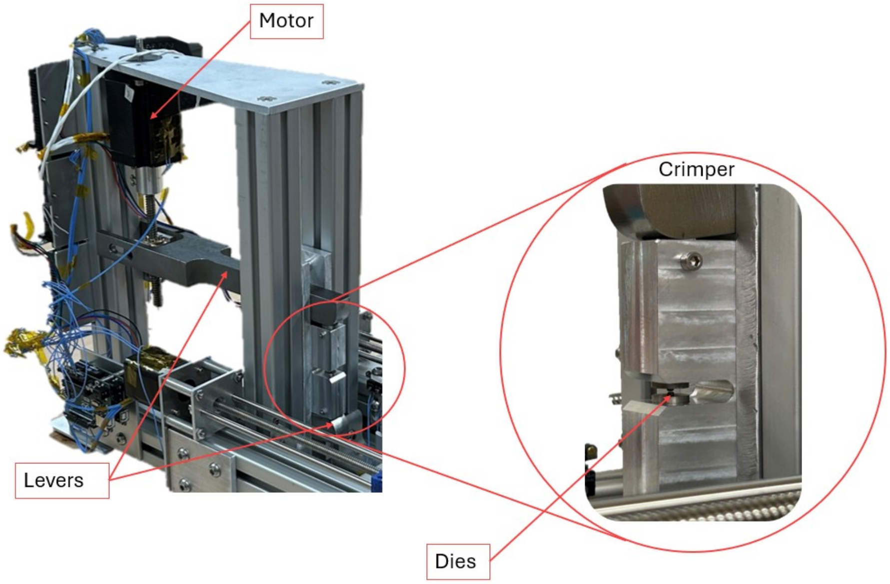

Fig. 6 Pressure Mechanism

Pressure is created using a motor, lead screw, and a lever which helps amplify the torque from the motor to reach the required force for the cold weld. The crimper uses dies to transfer the force to the aluminum members at one point from both sides of the joint.

D. Objectives and Requirements

MOCA's operation follows two main objectives and one secondary objective. For MOCA to provide a viable solution, the following objectives were created.

OB1.1 Functionality Guidelines: MOCA should follow the regulations stated in C3.
OB1.2 Main Operations: MOCA should perform cold welding.
OB2.1 Repeatable Functionality: MOCA should be a repeatable system.

Objective 1.1 ensures that MOCA will perform the required actions to compete within C3. Objective 1.2 ensures that MOCA will perform the necessary cleaning on the truss members to perform cold welding. Objective 1.2 also ensures that MOCA will administer the proper amount of pressure on the truss members to perform cold welding. Secondary Objective 2.1 ensures that MOCA will be able to perform the cold welding process in various locations on the members. Secondary Objective 2.1 also ensures that MOCA will be able to perform the cold welding process multiple times.

From the objectives, both system level and subsystem level requirements were determined. MOCA has ten system level requirements, as listed below:

R1.1 Operating Pressure: MOCA shall maintain the ability to perform cold welding in at most 0.4 torr.
R1.2 Mass limit: MOCA shall have a mass under 150 lbs.
R1.3 System Sizing: MOCA shall fit within a 15.75 x 15.75 x 35.45 inches rectangular prism.
R1.4 Shear Metric: MOCA shall produce welds that withstand 22.47 lbf.
R1.5 Safety Factor: MOCA shall withstand all applied forces to a factor of safety of at least 1.2.
R1.6 Remote Command: MOCA's software shall receive commands from a remote device.
R1.7 Power Interface: MOCA shall draw electrical power from a simulated Arkysis's Bosuns Locker Max's interface.
R1.8 Anti Seize: MOCA shall prevent cold welding of moving mechanisms.
R1.9 Data Acquisition: MOCA's software shall transmit data to a remote device.
R1.10 Code Language: MOCA's software shall be written in a common language.

MOCA has three subsystems; Mechanical, Electrical, and Control Software. Each subsystem has associated subsystem level requirements to refine MOCA's functionality. The Mechanical Subsystem has three requirements, listed below:

R2.1 Member Location: MOCA shall hold prefabricated members at the designated point with a tolerance of $\leq \frac{1}{32}$ in in each direction.
R2.2 Oxide Removal: MOCA shall expose at least $\frac{1}{8}$ in^2 of each member.
R2.3 Percent Deformation: the Mechanical Subsystem shall plastically deform the joint by up to 50%.

The Electrical Subsystem has three requirements, listed below:

R3.1 Voltage Range: The Electrical Subsystem shall operate at an input voltage between 5 VDC and 28 VDC.
R3.2 Sustained Power: The Electrical Subsystem shall draw no more than 300 Watts of sustained power.
R3.3 Peak Power: The Electrical Subsystem shall draw no more than 1000 Watts of peak power usage.

The Control Software Subsystem has eight requirements, listed below:

R4.1 Real-Time Data: The Control Software Subsystem shall log data at least once every five seconds.
R4.2 Command Limit: MOCA shall perform cold welding using less than 50 user input commands.
R4.3 Control Accuracy: The Control Software Subsystem shall regulate the actions of the Pressure Mechanism with a total margin of error within 15% of the depth of deformation.
R4.4 Code Functions: The Control Software Subsystem shall have code functions.
R4.5 Closed Limit Switches: The Control Software Subsystem shall display "1" if the limit switches are triggered on the serial port.
R4.6 Open Limit Switches: The Control Software Subsystem shall display "0" if the limit switches are open on the serial port.
R4.7 Temperature Monitoring: The Control Software Subsystem shall monitor the temperature of the heat generating components within the range of 40 degrees Fahrenheit to 155 degrees Fahrenheit.

R4.8 Temperature Reporting: The Control Software Subsystem shall report the temperature of the heat generating components through the serial port at least once every three seconds.

E. Design Trade Studies

Several design decisions had to be made to ensure that MOCA would meet all the requirements and remain feasible. The most critical ones were how pressure would be applied, how the oxide layer would be removed, and what type of joint was to be achieved.

For the pressure application, many options were discussed with the top runners being using an electromechanical spring or an electromechanical screw. Other options included pistons, a ramp, and a cam system. The chosen methodology was an electromechanical screw due to it being less complex than a spring and safer. MOCA then implemented a lever to amplify the force generated by the electromechanical screw.

For the oxide removal, the top option was actually a belt sander mechanism. Other options were laser cleaning, chemical cleaning, piezoelectricity, and scraping. Piezoelectricity was the runner up during the design phase, but the scraping mechanism was selected due to limitations in budget and the simplicity of using a wire brush over a belt sander.

For the joint type, there were only two options, a lap joint or a butt joint. Joint type was the most important study as the result from this could change the whole design of the system. The winning joint type was the lap joint due to it being simpler to work with when it comes to proof of concept. The butt joint would be better if MOCA was to test multiple different shapes and sizes. However to maximize simplicity and minimize extra processing such as cutting off the plastic deformation formed from a butt joint, the chosen joint was a lap joint.

III. Requirements

MOCA was designed around the critical system-level requirements identified in the team requirement listing and aligned with the COSMIC Track 1 challenge objectives. The main system-level requirements referenced in this design include R1.1 Operating Pressure, R1.2 Mass Limit, and R1.3 System Sizing, with R1.5 Safety Factor also serving as a key structural requirement. MOCA was designed to perform cold welding at no more than 0.4 torr, remain below the 150 lb mass limit, and fit within Arkisys's Bosuns Locker envelope. The current prototype dimensions are 22.5 in × 11.8 in × 15.6 in, which shows that the design remains within the allowable system sizing envelope defined in R1.3.

In addition to the system-level requirements, the design also reflects major subsystem requirements that define how MOCA is expected to function. For the mechanical subsystem, the critical requirements include R2.1 Member Location, R2.2 Oxide Removal, and R2.3 Percent Deformation. For the electrical subsystem, the main requirements include R3.1 Voltage Range, R3.2 Sustained Power, and R3.3 Peak Power. For the controls software subsystem, the key requirements include R4.1 Real-Time Data, R4.2 Command Limit, R4.3 Control Accuracy, R4.7 Temperature Monitoring, and R4.8 Temperature Reporting. Together, these requirements define the major mechanical, electrical, and software functions that MOCA must satisfy.

At this stage, MOCA is currently undergoing verification testing to insure that all requirements are met. The team has established verification plans and produced a working prototype that will be used to carry out inspection, demonstration, analysis, and testing for each applicable requirement. Initial analysis supports the design approach. For example, ANSYS analysis for the relevant structural case produced a factor of safety of 1.2809 (shown in Fig. 7), which supports compliance with R1.5 Safety Factor for that loading condition.

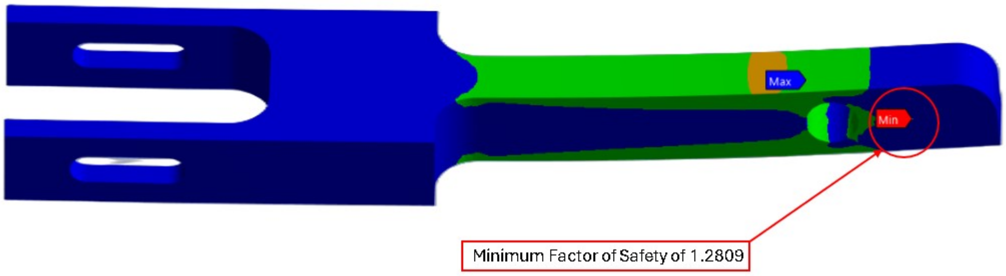

Fig. 7 Lever Arm Minimum Factor of Safety

Overall, MOCA should currently be described as a prototype designed to meet the critical requirements rather than a system that has already fully verified them. The requirement listing, prototype, completed analyses, and verification plans provide the basis for future testing and evaluation to determine whether MOCA fully satisfies the required system and subsystem performance criteria.

IV. Risk Assessment and Mitigation

The primary risks to MOCA are unintended collisions, code errors, motor skipping, tandem motor issues, carriage stalling, and misalignment during assembly because these are the problems most likely to affect motion and interrupt testing. Other non-critical risks include lead screw stripping, lead screw nut stripping, and brush binding, which could still hurt performance if they are not noticed early. To reduce these risks, all mechanical, electrical, and software components should be carefully inspected before testing begins. The lead screws, nuts, brushes, and carriage motion must be checked for wear, binding, and alignment, while the wiring and control code should also be reviewed before power is applied. During testing, the system should be monitored for skipping, stalling, synchronization problems, or unintended contact between parts. Overall, careful setup and close observation during testing will help reduce the chances of these risks affecting system performance.

V. Controls Software Architecture

MOCA's controls software code consists of functions that enable the full cold welding process. Since Arkisys Bosuns Locker has no restriction on the data communication protocol, MOCA can operate with most protocols, provided the Controls Software (CSW) code is updated accordingly. MOCA's CSW code is written in Arduino IDE and communicates with an Inter-Integrated Circuit (I2C) protocol as the team that designed and built MOCA was experienced in the protocol and coding language. MOCA will be collecting data on the limit switches to understand where in the cold welding process MOCA is operating and the temperature of the motor and stepper drivers to prevent overheating and damage to the system. To verify the CSW requirements regarding data handling, MOCA will output the data in the serial monitor a minimum of every five seconds. To verify the data handling requirements, MOCA will be videotaping the operation process and printing the timestamps of the data and comparing whether the data is printed on the serial monitor a minimum of every five seconds.

In the CSW code, MOCA uses the sensors to gather data and allow the cold welding process to be split into multiple functions. MOCA utilizes two Arduino UNOs, one for the stepper motors and drivers, and another for the limit switches and temperature sensors. Both Arduino UNOs are programmed to read the serial monitor and react accordingly. The limit switches will print "0" or "1" onto the serial monitor, allowing the technician to input the command into the serial monitor. The code allows for the cleaning mechanism to be run an inputted amount of times to allow the oxide layer of the metal members to be fully scraped off. Another hard-coded variable is the number of dimples in the members. Currently, the hard-coded number of dimples per welded joint is three, which can be adjusted to the user or application. After testing, the code will be altered to finalize the number of dimples and the number of runs the cleaning mechanism needs. MOCA's I2C interface allows the two Arduinos to communicate to each other and enable the cold welding process with inputted commands from the serial monitor.

VI. Innovations

Engineering efforts around cold welding are normally aimed at avoiding inadvertent welding of release mechanisms or other metallic moving parts where such welding could cause mission failure. MOCA distinguishes itself from previous research by leveraging the non-oxidizing space environment to develop cold welding into a reliable manufacturing technology. ASTROBEAT [2] is another innovative investigation of cold welding for a constructive use by plugging holes from hypervelocity impacts. ASTROBEAT's mission of spacecraft repair by cold welding differs from MOCA, where MOCA instead looks to create new structures in space of nearly any size and shape limited only by the provision of the raw material. The MOCA prototype was scoped only to demonstrate cleaning and welding, however, and so a few innovations were not pursued.

As part of the de-scoping process MOCA eliminated potentially innovative ideas. One such idea was to use a laser cleaning system to remove the oxide layer from the test samples. While MOCA had a sponsor potentially interested in supplying the laser system, the complexity of shining the laser through a window on the vacuum chamber was deemed unfeasible in the time available. Additionally, gases released from the laser cleaning operation could damage the chamber's pump. Despite the challenges that the use of a laser presented to MOCA, it may be a more appropriate cleaning method than scraping with a wire brush when performed in the real space environment.

VII. Lessons Learned

A. Innovative Ideas

The goal of MOCA was to develop a lower-energy method of creating large truss structures in orbit than conventional means. Cold welding is a known phenomenon in which two similar metals in vacuum tend to bond together. MOCA chose to take advantage of cold welding, traditionally seen as problematic and to be avoided, as a primary method of orbital construction.

To fully take advantage of cold welding, MOCA sought different methods of cleaning metallic members of any contaminants or coatings that would impede bonding. MOCA considered the use of lasers as a means of removing the surface layer of the metal. However, MOCA decided not to pursue laser cleaning due to complexity concerns and budget limitations.

MOCA also desired to explore different means of communicating between the assembly and command computer. Utilization of laser communication was proposed to achieve fast and high quality data transfer. However, laser communication would add additional complexity to MOCA's design and many members of the team had little experience with the technology. MOCA decided to settle with more familiar communication methods.

B. Technological Limitations

In the early stages of MOCA's design, over-scoping was a major concern given the time and resources available. Although MOCA competes in C3, it is also a university capstone project. MOCA was required to deliver a functional prototype in addition to the concept within the same year-long time frame. MOCA was rapidly de-scoped, most notably from an actual product to be launched and used in space to a demonstration of the process for others to scale and build upon.

One major area of development is the Pressure Mechanism. Large space structures will require MOCA to use larger members, and the amount of force needed to create a strong cold weld increases with member thickness and varies with material. MOCA was designed with Aluminum 3003 as the member material, which is softer but far less common for in-space structures than Aluminum 6061. If MOCA's process is to be adopted for orbital manufacturing, a more versatile and powerful Pressure Mechanism will be necessary.

Another area of interest lies with the Alignment Mechanism. With the current MOCA design, the Alignment Mechanism can only position the two truss members axially, and can only overlap them at a 180 degree angle. The lack of angular control severely limits the MOCA's effectiveness. However, a more pressing issue is that the Alignment Mechanism cannot support creating structures with more than two members. Development of a new Alignment Mechanism that can support multi-membered joints and control over member angles will be necessary for a final product.

Finally, the Cleaning Mechanism has no means of containing the particles produced by the cleaning brush. With the demonstration, we considered the Bosuns Locker as the main means of preventing the creation of orbital debris. However, the current containment method will not be sufficient for a machine that creates multi-membered space trusses, and thus a better solution needs to be developed.

C. Challenges Faced

When creating the current design for MOCA, several challenges arose. The first major challenge came in the form of unforeseen conflicts between the Computer Aided Design (CAD) files and the physical assembly. MOCA utilized countersunk screws to fasten plates to extrusions and staying flush to the plates. However, how the thickness of the plates affect the countersunk screws was not considered in the design phase, leading to the countersunk screws protruding through the other end of the plate. To avoid the issues caused by this, the button head screws and washers were used in place of the countersunk screws for areas where countersinking was desired but not mandatory. Additionally, the cleaning brushes purchased to use on MOCA did not perfectly match available CAD files online. Thus, several modifications to the Cleaning Mechanism had to be made to support the actual brush geometry.

The second major challenge was determining a way to test the effectiveness of the Cleaning Mechanism in removing the oxide layer of metals. Due to MOCA's Earth-based testing and resource limitations, it is difficult to measure the percentage of the cleaning area is successfully freed of oxide, as Aluminum tends to oxidize quickly in atmosphere. MOCA decided not to measure oxide removal directly, but instead marking the cleaning area with a visible coating and noting how much of the coating is removed after passing the Cleaning Mechanism.

The third major challenge was determining ways to test weld quality. While testing the strength of welded members under load was a given, it does not provide significant insight into how well the two Aluminum members bonded. MOCA decided to conduct dye-penetrant tests to welded members in addition to destructive loading tests in order to more readily see the effects of cold welded joints on both a macroscopic and microscopic level.

VIII. Conclusion and Recommendations

While MOCA develops cold welding as an in space manufacturing process, the prototype built is only suitable for producing welded samples for testing the welded joint's strength. There are a few areas where future development could take the cold welding concept to a process that produces a manufactured product. One such area is the provision of the raw material, possibly as flat stock or wire on a spool. Another area is the forming and cutting of the raw material to shape welded sections into desired structures. Additionally, a method of preparing the material's surface for the weld which removes the oxide layer without producing contaminates or debris will be needed to bring MOCA to the space environment.

In most spacecraft design projects, the tendency for metals to cold weld in vacuum is approached as a risk to be avoided, but MOCA will show that this property can be uniquely leveraged to build structures in space. Although MOCA is a small scale prototype, it can be scaled up in future development to build larger structures by exploiting its strengths. Cold welding requires much less power than welding by melting materials together, and the process is also cleaner than traditional fusion welding. Furthermore, MOCA will require fewer launches to build large trusses and other structures compared to previous methods, which will reduce both the cost and environmental impact. The innovative application of cold welding as a manufacturing process presented by MOCA is poised to add a new capability to the future of in space manufacturing.

Acknowledgments

MOCA acknowledges Dr. Kaela Martin and Dr. Dawn Armfield for their input and encouragement throughout the development of this project. MOCA also acknowledges the C3 COSMIC Capstone Challenge for providing the idea prompt that helped shape the direction of this project. MOCA also acknowledges Undergraduate Research Institute for providing MOCA with additional funds. MOCA would like to acknowledge Prescott Steel for their contribution of the steel needed for the levers in the Pressure Mechanism. MOCA would also like to acknowledge Ben Grieger and Abigail Storey for their contributions to the design and modeling of MOCA.

References

[1] Agwu, U., Atre, R., Heying, J., and Rome, J., "2025–26 COSMIC Capstone Challenge – Information Packet – Initial Release," Information Packet COSMIC-E01-WD005-2025-A, Rev A, Consortium for Space Mobility and ISAM Capabilities (COSMIC), July 2025. URL `https://cosmicspace.org/c3`, initial Release, July 17, 2025 Available online: `https://cosmicspace.org/wp-content/uploads/2025/07/C3-2025-26-Information-Packet-July-2025.pdf`.

[2] Barilaro, L., Lopresti, S., Olivieri, L., and Wylie, M., "ASTROBEAT: Advancing cold-welding technology for in-situ spacecraft repairs," *Journal of Space Safety Engineering*, 2025. https://doi.org/https://doi.org/10.1016/j.jsse.2025.08.006.