Design and Feasibility of an Autonomous Wire Bender Payload for On-Orbit Truss Fabrication

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Expanding humanity into space will require the construction of significant habitats- serving as research labs, housing, and recreational spaces. The cost of time, money, and people to construct large structures in space is prohibitively expensive, with the only large structures in space designed for extended human habitation being the International Space Station. Servicing, assembly, and manufacturing processes must be developed to facilitate this in space. This paper presents the early conceptual design and feasibility analysis of an autonomous wire-bender payload capable of bending wire to form modular structural units. The payload integrates in-space manufacturing operations- wire drawing, twisting, bending, and cutting- to form modular structural units autonomously from continuous segments of stainless-steel wire in Low Earth Orbit.

I. Nomenclature

ISAM = In-Space Servicing, Assembly and Manufacturing
COSMIC = Consortium for Space Mobility and ISAM Capabilities
C3 = COSMIC Capstone Challenge
LEO = Low Earth Orbit
AWG = American Wire Gauge
SS = Stainless steel

II. Introduction

A. Background and Motivation

In order to ease the expansion of humanity into space it is necessary to create large structures for habitation and research. With the current methods for in space construction these structures are prohibitively expensive to make having high cost monetary, time, and in human risk. For example, the International Space Station (ISS) took a total of 13 years to complete starting in 1998 and being completed in 2011. Over this 13-year period approximately $150 billion over the course of 40 assembly missions. Each mission had the purpose of placing together prebuilt modules into the final ISS. These modules were assembled on the ground and then shipped to low earth orbit. However, if the resources to construct these components' on site' had existed the station could have been constructed in far less time and far cheaper due to the exorbitant shipping costs with space flight as well as the development of ISAM technology for sustainable expansion into space

B. Problem Statement and Objectives

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Construction of large structures in space is prohibitively expensive. In order to help remedy this a device is needed that can fabricate sturdy trusses and booms out of common stock, quickly, accurately, and entirely autonomously in a LEO environment for use in large scale construction in space.

C. Technical Impact (1.1)

The Space Wire Bender would use modified versions of existing rotary draw bending designs to fabricate trusses and booms on site easing the creation of large-scale satellites. The design is adaptable, allowing it to be used for a variety of different materials and to create a wide range of different shapes including various prisms, cubes, and pyramids. The Space Wire Bender would function as one step in a satellite powered assembly line potentially to fabricate modules but could also be used for any bending process currently done on earth.

III. Conceptual Design

A. System Overview

-Description of individual operations
-Integration of these operations into a capability
The objective is to create large scale trusses and booms. In order to do this we have 4 processes

1. Rotator
   a. Large gear located on the back of the device holds the spool of material, this allows the spool to be rotated 360 degrees
2. Feed
   a. Rollers pull the material from the spool into place for other processes along with the bending head deployment allowing for accurate positioning
3. Bender
   a. A rotary draw bender bends the material to the desired angle in both clockwise and counterclockwise directions
4. Cutter
   a. An enclosed cutter cuts the wire so the final truss can be removed from the device to be used in other processes. Contains and stores all generated debris within

B. Design Requirements and Constraints

The device must be able to fit into a BCT X-Sat Bus in the dual solar array configuration, this means that it must have dimensions less than 17.0” x 16.4” x 27” have less than 70kg of mass and draw less than 444W. It must also be fully automated and able to complete tasks with little to no user input the device must also be able to draw from the spool rotate the spool and complete bends to fabricate the trusses it will be able to complete bends from 0.1 degrees to 120 degrees on 0.203” diameter wire and complete a full 18” cube truss structure in 90 seconds or while functioning in the vacuum, microgravity, high radiation environment of LEO.

C. Required Elements

Analyses have been conducted to verify that the payload meets the requirements and constraints previously outlined.

Payload Mass		
Component	Mass (kg)	Mass (lb_m)
Spool (T6-6061)	8.9	19.7
Wire (400' AWG 4, 316 SS)	20.4	45.0
Housing (Ti-6Al-4V)	17.5	38.7
Feed	0.91	2.02
Rotator	4.95	10.92
Cutter	0.31	0.68
Bending Head	0.85	1.87
Bending Deployment	5.06	11.16
Total Actual	58.8	130.1
Target	70.0	154.4

Table 1: Payload Mass

Payload Volume			
	Length (in)	Width (in)	Height (in)
Actual	26.6	11	11
Target	27	16.4	17

Table 2: Payload Volume

A table of the payload's actual mass, power, and volume are detailed above. Upon inspection, it has been determined that these figures are within satellite bus constraints and validate them.

1. Demonstrate Capability Using Operations (1.4)

The bender technology has the capability to feed, rotate, bend, and cut our selected material, 316 stainless steel wire with .204" diameter. This essentially transforms raw material into usable truss blocks that can then be assembled to create even larger structures when successfully bound together.

The rotator is a large gear located near the rear of the technology which allows for full 360-degree mobility so that the wire can be rotated into any orientation to successfully create the desired bend. The feed mechanism is comprised of plain roller mechanism that pulls the material from the spool allowing for accurate drawing and positioning necessary to make desired bends.

The feeder and rotator work simultaneously continuously drawing the wire and rotating as the bender executes bends. The bender head is made from D2 cold working steel typical for rotary bending machines. This bending head mechanism is allowed to rotate fully counterclockwise and clockwise allowing for full range bending in either direction to any desired angle. Our cutter is the last step in the process while the bender, feed, and rotator perform the desired operations to complete desired bends finally a mechanical cutter executes its function allowing for the separation of fully completed blocks from the technology so that the process can be repeated begin manufacturing of more blocks.

2. Design for Launch (1.4)

Design for Launch Loads (Shock, vibration, acoustic)

Our technology is designed to survive launch loads by ensuring each component is created using materials already approved and previously chosen for similar low earth orbit satellite missions.[1] The compact design is meant to fit well within the fairing to be secured further by the usage of straps or other securing mechanisms to hold it in place. The entire housing is made from Ti-6Al-4V to ensure structure stability and strength where the working components are made from D2 cold working steel while the material to be bent is simple 316 Stainless steel .204" diameter wire. Our technology has been adequately thought out and based on previously successful launches of satellites made from similar materials. Of course, before launch this will be verified utilizing various tests of the mechanical, thermal, and functional variety applied to payload to guarantee the technology works and survives as intended post launch.

3. Design for Low Earth Orbit

Design for Moving Parts in LEO (Wear, lube/outgas, overheating)

The bender is designed to mitigate wear, internal debris, lubrication outgassing, and overheating of moving components. We began with careful material selection, avoiding materials like pure tin, which form whiskers that can create debris and harm vital components [1]. Moving components such as gears and rollers will be made from high-durability materials like tool steel and titanium for wear resistance. To further prevent internal debris, wire cutters, and gears will be fully enclosed in a containment unit, ensuring that shavings remain isolated. The gears are lubricated with space-grade Molybdenum Disulfide (MoS2), chosen for its low outgassing and friction properties [2]. The lubrication will be contained to prevent contamination from outgassing over time.

In addition, thermal control is critical to prevent overheating and thermal expansion, which could lead to mechanical failure of the system's moving parts. The wire bender's components, which include materials tool steel, and titanium, will be designed to withstand temperature fluctuations in space. Given the power constraints of the payload, the bender will use passive strategies such as sprayable thermal coatings to regulate surface properties. At the same time, multilayer insulation (MLI) will mitigate external temperature fluctuations on system components [3]. These measures ensure reliable operation in LEO's harsh environment, safeguarding vital components of our system, such as motors, sensors, and the exposed bending head deployed outside the payload.

Design for Thermal in LEO (Thermal control, thermal expansion, day/night cycling

The design had to have multiple steps in protecting itself from the thermal expansion and build up over time during operation in LEO environment, such as the chosen insulations used to regulate heat and become flexible when needed for its expansion as the layered stack set up has been used in industry as the best form of external thermal protection. The MLI will be monitored with sensors in order to help regulate temperature and help manage the thermal systems. The inner insulation will control the radiation distribution within the Bender taking the smaller size of the bender and small surface area of the bender's wall makes it so that moving heat around the system is quick and simple. The gyroscope of the bus will be the major contributor to exposing the bender to direct sunlight, radiation, and alternating of position when necessary, using sensors.

Design for Outgassing in LEO

The Bender technology by design is meant to avoid outgassing. The structure is basically a modified rotary wire bender which is practically made entirely out of metals which are exceptionally less susceptible to outgassing than other materials. The entire housing mechanism is made from Ti-6Al-4V for proper strength and storage to house our technology, while the working components are D2 cold working steel, all of which are metals that do not experience outgassing to a significant degree. For our rolling mechanisms and lubricant, we chose Molybdenum Disulfide which is a space grade lubricant that does not outgas and opted to used plain rollers which are designed to not outgas as well. So, the main components and small components are protected from outgassing by design and in the case of areas that need sealing we can use low outgassing approved silicon.

<u>Design for Micrometeorites in LEO</u>

The Bender has had Micrometeors considered in the form of its outer layer design that keeps its body small and objective focus making it small and harder to impact as well as the shape giving it a turtleneck shape that helps prevent debris and micrometeorites from entering.

<u>Design for Radiation / EMI in LEO</u>

The design for radiation is reflected in two parts the external and internal. Externally we will be using a Thermal Blanket or Multi-Layered-Insulation (MLI), This layer protection comes in this order Aluminized Kapton, Dacron Mesh, Beta Cloth, and Polyimide based adhesive tape to seal edges and give it a final sealing. These specific materials were chosen after reviewing similar space launches in LEO environment and with MLI being the most common external protection method for space craft. They boast high temperature Ranges and have a great Amount of flexibility and lifetime durability that fits the timeline that our bender must remain in operation. The internal insulation will use a combination of thermal pylons and PCM used to transfer the heat around the entire machine and into the vents. However, our design hasn't considered the specifics of the inner electronics and heat produced, as we focused mainly on the operation of the bending apparatus.

<u>Design for Atomic Oxygen in LEO</u>

The MLI as previously mentioned already accounts for the AO in the LEO. The outer layer of Kapton is known for its resistance against erosion, and friction created from the AO atoms moving about. The Feed Material itself has sufficient resistance to AO and is not susceptible to its effects over long periods of time, however as an extra precaution we have covered the stock during most of the process to limit the exposure to the open environment.

4. Truss Design for Low Earth Orbit

Our truss design involves creating a truss from truss blocks made up entirely of a single wire bent into the shape of a cube. These blocks would then be assembled or attached together after the manufacturing process of the blocks is completed to create one long continuous truss from these building blocks. The structure of the blocks is made from 316 stainless steel with a .204' diameter. Manufacturing these blocks in space allows for the creation and assembly of a truss in practically any shape, any size and in a relatively quick manner without having to worry about the structure needing to survive launch.

D. Trade Studies (1.7)

Desirable Material properties	Material Considerations				
	304 Stainless	A286 Stainless	Hastelloy C	Copper	316 Stainless
Strength (2)	1	2	2	1	1
Bendability(3)	3	1.5	1.5	3	3
Stress-Corrosion Resistant(3)	2	3	3	3	3
No Prior Work Needed (1)	1	1	1	0	1
Score	7	6.5	6.5	7	8

Table 22 Material Selection Trade Study

Selection of material is critical as our environment dictates what materials are allowable for our application of technology. Our material trade study evaluated a series of promising metals and alloys against critical criteria to allow us to clearly highlight a material as the most applicable to our technology.

On the left we have our criteria each that have their own weight based on how important those criteria are to our application ranging from 1-3. 1 being the least important and 3 being crucial for design purposes. For example, bendability has a weight of 3 due to the fact that our material needs to be ductile enough to be bent. Strength has a 2 because it's slightly less important than ductility since we are operating in space and don't need to fight against forces such as gravity, and pressure building up from things stacked on top of each other. No prior work is rated only as a 1 due to this not being exceptionally crucial to the design aspects. When our materials are evaluated against all these different criteria 316 Stainless steel was found to be the most appropriate material to use within our technology to make trusses out of. So, from our material trade study we managed to decide that 316 was the most appropriate material to move forward with our technology.

Type of Roller	Roller Weight	Durability	Power Requirement	Load Capacity	Maintenance Needs	Total Score
Belt Driven Roller	2	1	3	4	2	12
Chain Driven Roller	1	5	2	5	2	15
Motor Driven Roller	4	5	2	4	4	19

Table 33 Feed Mechanism Trade Study

The feeding system is essential to wire delivery, guiding it from the rotator to the bending head. A decision matrix (Table 3) evaluates three types of titanium feed rollers: belt-driven, chain-driven, and motor-driven. Each was scored from 1 to 5, with five being most favorable. Motor-driven rollers ranked highest, scoring 19 out of 25 and outperforming both alternatives.

Maintenance was a key factor in the decision. Low-maintenance components are critical since the system operates in orbit and is non-serviceable post-deployment. Motor-driven rollers eliminate issues common in belt systems, such as stretching or cracking due to rubber degradation in space. Chain-driven rollers are also prone to snapping or buildup in chain gaps, leading to derailing and maintenance needs [4].

Another advantage is that motor-driven rollers require no lubrication, a significant benefit in space, where lubricants in chain-driven systems can vaporize, creep, or deplete, risking contamination of other components [2]. Operationally, the system uses stepper motors to drive the titanium rollers with load capacities between 15 and 65 kg. Stepper motors are used because they offer precise control and, under low-duty cycles, can last up to 20,000 hours, well beyond system requirements. Depending on the load, they typically deliver 0.5-1 Nm of torque and consume as little as 10-25 watts per roller [5]. A redundant motor ensures continued operation in case of failure.

3Question: Which bending process is best for the payload

Criteria

- Speed
  - o How quickly can the bending process be completed
- Component complexity
  - o The complexity of the bending device as a whole
  - o Weight of 2
- Part Complexity
  - o The complexity of products the style of bending can produce
- Angle Range
  - o The range of angles possible with the bending process
- Low die Number
  - o How many dies are needed to complete the process
- Size
  - o The physical size of the bending

Each Criteria is scored on a one to 5 scale then multiplied by the weight value for the criteria shown in parenthesis

Requirement	Air bending	3-point bending	Rotary Bending	Roll Bending
Speed(1)	Very Fast	Middling speed	Fast	Fast
Component complexity (2)	Very Simple	Moderately Complex	Moderately Complex	Simple
Part complexity (4)	Simple Fabrication	Middle Fabrication	Complex Fabrication	Simple Fabrication
angle Range (5)	Medium Range	High Range	Large Range	Medium Range
low die number(3)	Many Dies	Few Dies	1 Die	Many Dies
Size(3)	Small footprint	Medium Footprint	Small Footprint	Medium Footprint
Total	43	53	75	50

Table 44 Bending Mechanism Trade Study

With the criteria in mind the best choice was rotary draw bending, it uses a relatively simple bending head design that can create a large range of bend angles while only using one die for all angles, when compared to roll bending which is just as fast if not faster its larger form factor and necessity for multiple different dies meant it was not as well suited for this application. Rotary draw bending beats out all other options in most criteria matching or being slightly worse than others in only a few

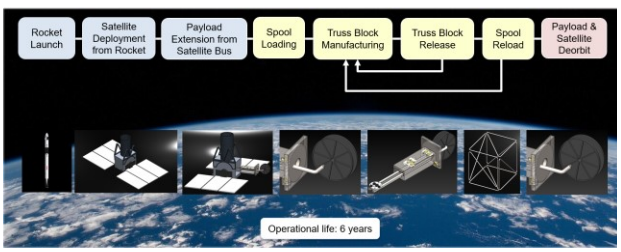
Criteria	Mechanical Cutter	ECM (Electrochemical Machining)	Grinder
Debris creation	Small debris, Debris Collector	None	Debris collector apparatus
Score (1-3)	2	3	1
Speed	Fast	Slow	Slow
Score (1-3)	3	1	1
Size	Compact, adjustable	Large	large and heavy
Score (1-3)	3	2	1
Power	Low power, Efficient	Medium power	Low power
Score (1-3)	3	1	3
Material Compatibility	works with some workable metals	Most materials	Most materials
Score (1-3)	2	3	3
Total	13	10	9

Table 5: 5Cutting Mechanism Trade Study

When deciding on a method for cutting material after the full bend is made, we focused on 5 different criteria to meet within the restrictions. The debris created was vital since our system would have to produce some number of debris and mitigating the amount created was priority which brought us to the conclusion that a (ECM) Electrochemical machining device would be most suited because it created no debris however it had many flaws such as a huge size requirement that would have broken our volume and even our weight restrictions. The ECM would have also required much more complex set up, including Maintenance. And finally, the power consumed by one of these machines was outside of the Power capacity and would overcomplicate our system operation. So, a much simpler Guillotine design was chosen over the ECM which met our requirements and only produced minimal debris which is being taken care of a magnet.

IV. Concept of Operations

A. Storyboard (2.2)



Detailed above is a storyboard of the payload's operations from launch to deorbit. The payload, housed on the BCT X-Sat Venus Class Bus, is launched aboard a Falcon 9 rocket. After reaching space, the satellite is deployed from the rocket's fairing and is inserted into orbit. Upon orbital insertion, the bus's payload bay is opened, and the payload is extended via an extension mechanism. At this point, the payload can begin pre-manufacturing operations. An outside manipulator loads a spool onto the spool arm. After spool loading, the bending head is extended outside the payload, and the payload may begin manufacturing operations. The payload performs a cycle of truss block manufacturing, truss block release, and spool reloading. After an operational life of 6 years, the payload is decommissioned and deorbited by the satellite bus.

B. Data Handling and Communications (2.4)

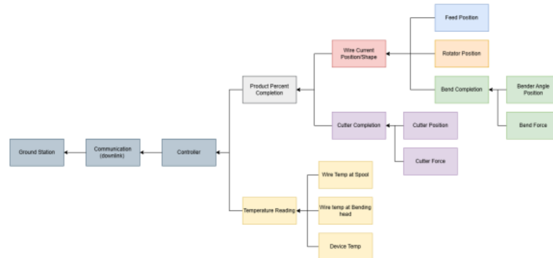


Figure 2: Data flow chart for Space Wire Bender

Telemetry data from the variety of sensors on the system will be used to correctly identify the percent completion of the current project and monitor for errors in its fabrication this information will be downlinked to

V.Risk Analysis and Plan

Risk Identification and Mitigation Strategies (1.5)

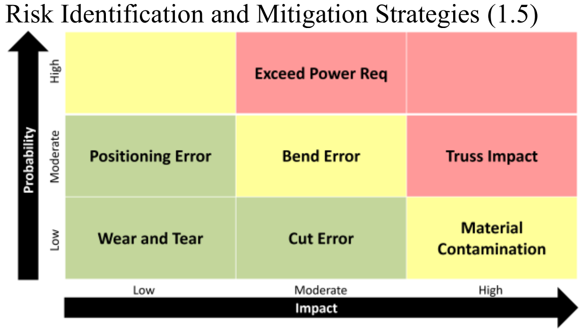


Figure 3: Risk identification chart

Wear and tear is what on the ground would be regular wear and tear due to use over time. To avoid this from being a problem for our projected life span the components have been designed to be under the point where they will suffer ill effects from repeated use over the operation life

A positioning error is when the wire is not properly positioned to complete the desired bend at the desired position. To avoid this, sensors are in place that keep track of the wires current position and if the wire is over/under fed or over/under rotated the process will be reattempted till the desired position is achieved. If the process is repeated and still not completed, then the process will be halted in order to protect the functionality of the satellite A cut error occurs when the cutter cannot successfully cut through the wire or becomes jammed. To mitigate this the cutter has a similar process that the Positioning Error has where it repeats the process attempting to successfully complete the cut, if it is unable to after repeated attempts it halts processes and returns to idle to protect the satellite. A Bend Error occurs when the bend is either under or over the target angle. As with the previous two errors the bender will reattempt until the controller tells it not to, to protect the satellite

Material Contamination is the wire that is being used for bending having some form of contamination, this could be the material not being homogeneous, having some form of surface contaminant, and/or being of otherwise inferior quality. In order to avoid this the wire will be rigorously tested before it is loaded into the Space Wire Bender to ensure it is of sufficient quality. In order to avoid exceeding the power requirement the Space Wire Bender has been designed to operate well under the supplied power by the bus this way in case any component must use extra power for whatever reason it can still operate cleanly.

Lastly Truss impact is when the manufactured block strikes the satellite during a bending, rotation, or feed process. To avoid this the bending head is extended far from the satellite so that the in progress block will never come near striking the satellite during its fabrication.

Fault recovery plan (2.3)

Debris mitigation plan

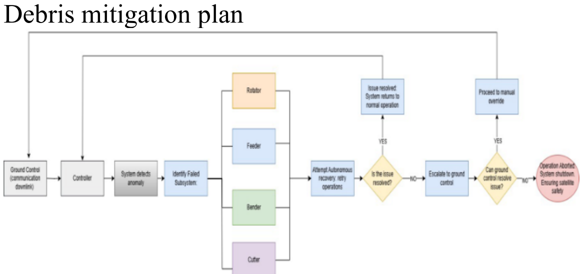


Figure 4: Faulty Recovery Plan Flow Chart

The Safety of the satellite is a priority; therefore, our system has a fault recovery process designed to prevent damage to the satellite. Figure 4 provides a step-by-step process of the fault recovery plan through a workflow diagram, from fault detection to system resolution or complete shutdown.

The system enters a fault recovery process when it detects an anomaly through the sensor readings that are outside the expected range or when it detects an obstruction of the wire. This triggers a diagnostic procedure and real-time data on the controller to identify the cause and subsystem, whether it's the rotator, feeder, bender, or cutter. This real-time monitoring ensures that the system pinpoints the issue and responds promptly. Once the issue is diagnosed, the system will attempt autonomous recovery by retrying the operation or adjusting parameters, such as rotation angles, bending force, or realigning the wire. If the issue is resolved, the system returns to regular operation, minimizing downtime and supporting system continuity.

However, the issue is escalated to ground control via communication downlink if autonomous recovery fails. Ground control receives detailed diagnostic information, including controller and subsystem status sensor data, enabling remote troubleshooting. If ground control can resolve the issue, they will perform a manual override to restore regular operation. If ground control cannot fix the problem, the bending system is shut down to protect the satellite. While this scenario results in mission loss for the bending system, it prevents damage like electrical faults to the satellite or its payload.

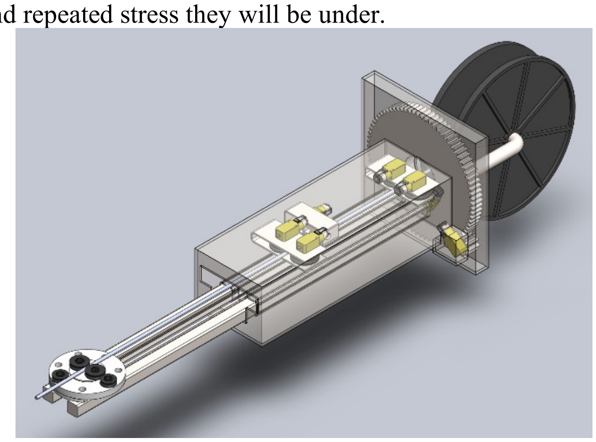
Debris Mitigation Plan

In case of a system failure, all debris-generating components are automatically designed to transition to a fail-safe mode. Cutting operations are halted, and containment remains enclosed to prevent wire-shaving release. Other sealed compartments, including motors and electrical systems, are designed to maintain integrity. These protective measures include passive components, such as sealed barriers around the deployment system's gears. This ensures that even in scenarios like power loss or mechanical jams, no particulate matter escapes, safeguarding both the satellite and the orbital environment.

VI. Discussion and Future Work

A. Prototype Mission Feasibility (1.2)

Figure x shows the bender in completion and all of its individual sub systems, each of these are comprised predominantly of titanium with some high stress parts being made of tool steel due to the high and repeated stress they will be under.



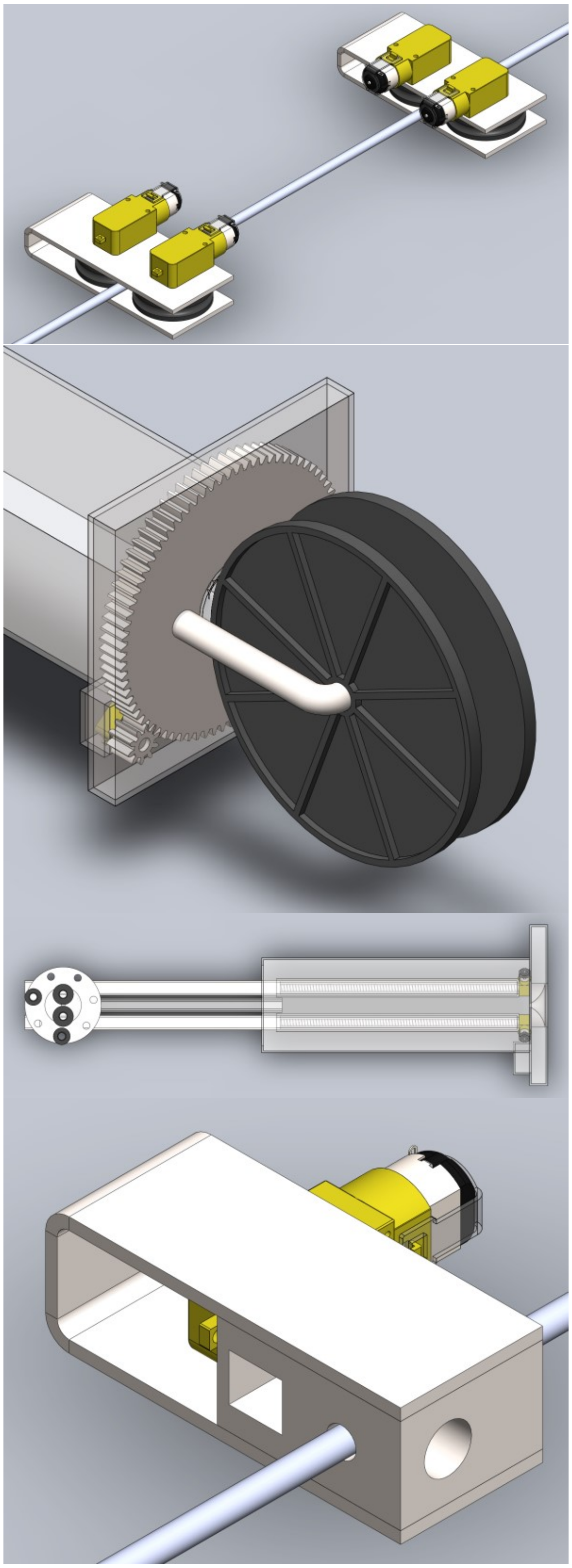


Figure 5: Isometric view of (from top to bottom) Full Space Wire Bender, Feed mechanism, Rotator Mechanism, Bender mechanism with extender, Cutter Mechanism

Due to the extender and the otherwise small form factor the Wire Space Bender is able to fit entirely into the payload bay of the BCT X-Sat Venus Bus while remaining well under the weight requirements even when launched loaded with a full spool of steel allowing it to start fabrication almost immediately. The complex multilayer insulation of the system protects it from radiation and temperature of the space environment ensuring it is able to function for its entire expected functional life if not longer.

The Space Wire bender uses predominantly existing components meaning aside from the housing and gears and modifications to this existing components the fabrication of the device would be relatively easy and affordable

B. Tech Gap Assessment (3.2)

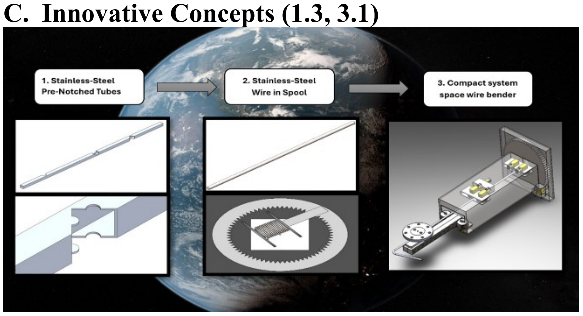
Sub System	Tech Readiness
Feeder	Level 6
Rotator	Level 6
Bender	Level 4
Cutter	Level 4
Motors	Level 6
Attitude Control	Level 8
Data Handling	Level 8

Table 6: Technology Readiness for subsystems

The main technology that needs to be developed for this process are the bender and the cutter, for both subsystems there currently exist examples on the ground that theoretically would function well in the space environment however they have yet to be tested in similar environments or the environment itself. While the on-ground versions are commonly used there may be unforeseen issues that arise should they be implemented without proper testing. The conceptual bending head used in this design supports the wire in all three axis to ensure that the bend performs properly. However current models on ground lack this the conceptual bending head used in this design supports the wire functionality.

As for the cutter the main worry is debris creation while this is a problem on the ground due to gravity and atmosphere things such as vacuums, funnels, and regular maintenance can be used to ensure that debris is not a problem in its operation. While our cutter head design does take this into consideration containing the created debris it would still need to be tested to ensure that it can sufficiently contain the debris. Lastly software would need to be developed to ensure the proper and efficient operation of the Space Wire Bender, while currently existing CNC software could be used as a base line for this process due to the unique environment this would not be sufficient in managing the telemetry data provided and ensure the completion of the processes to a sufficient degree.

C. Innovative Concepts (1.3, 3.1)



The three most creative ideas for this concept began with the first idea of a tube bender to create structure in space. The concept of bending material in space started with pre-notched tubes that would be used to construct two- and three-dimensional structures. This approach was initially appealing because it could simplify the bending process through pre-engineered notches, allowing for precise and repeatable bends.

However, significant challenges emerged as the team delved deeper into the concept. The pre-notched tubes must be manufactured on Earth and then sent on payload, increasing substantial storage space and weight, which was incompatible with the strict volume and weight constraints of the BCT X-Sat Venus bus. Additionally, the rigidity of the tubes limited the versatility of the structures that could be built, prompting the team to seek a more flexible and efficient solution.

This led to the development of a second concept: using stainless-steel wire stored on a rotating spool. Unlike the pre-notched tubes, the wire offered a compact and continuous 400 feet of material supply. This significantly improved storage efficiency and would enable the wire to be sent up with the payload. The wire being 0.204-inch in diameter is optimal for bent but maintaining its structural integrity and constructing precise trusses and booms. The wire spool flexibility allowed for greater adaptability in design, making it better suited for the dynamic requirements of space applications. This transition marked a pivotal moment in the project, as it addressed the initial concept's limitations and allowed us to continue with the bending system for in-space manufacturing. The wire-based bending system demonstrated how innovative material choices could enhance functionality and efficiency,
aligning more closely with the project's goals.

The third and most creative idea is conceptualizing an integrated wire rotator, feeder, bender, and cutter system. Initially, the team envisioned a system capable of feeding, rotating, and bending materials, but the specifics of how these functions would work together were undefined. As the project progressed, the team explored mechanisms to integrate these components into a cohesive system that would function in space. This integration aimed to streamline the bending process and reduce system complexity and size, as many systems on Earth are substantially larger and weigh a lot.

However, designing a bender for space use faced significant challenges, particularly in ensuring precise coordination between the rotator, feeder, bender, and cutter while adhering to the strict constraints of volume, mass, and power. Despite these hurdles, the concept of the bending system came together and can significantly contribute to building structures in space. This system's compact and modular design makes it highly adaptable for integration with other autonomous systems.

D. Challenges (3.3)

The first and largest hurdle that the team had to overcome was correctly defining the scope of the project in a way that kept the project both viable yet innovative while being within the realm of possibility for our team. In the beginning discussions of brainstorming, we initially wanted to create robotic manipulators that could hold and weld points of interest either to repair or replace parts like framing of satellites. The team quickly found that due to power constraints this was simply not feasible with the constraints of the project. This idea was ultimately scrapped and the team had to pivot onto a new idea where we simplified the actions being performed by our technology.

Of course this was not the only hurdle the team faced, largely at the start of the project there was trouble with organization, at first the project was thought to be a 10-person collaboration if the team could successfully fully define a project that was adequate to require a 10-person team. However, we were advised that organizing and collaborating with 10 people would be difficult, especially for this type of project and when reoccurring meetings and constant stream of communication is required. The team ultimately failed in creating an idea that required an entire team of people. The advisors and the team concluded that splitting the team into 2 groups of 5 to overcome the issue of such a large team and make defining a project more manageable for all was the best choice to make for the sake of time.

The last large hurdle was finding a starting point for our technology to be applied to space. While bending is a simple process a lot of Earth benders are built robust and universal to handle a range of widths of wire and different material to be bent any which way. This makes benders here on earth very large and very power intensive. We needed the simplest version of bending that could be downscaled and focused on bending one material within the constraints of our project. Luckily this hurdle was overcome through research where our team found a type of bender that we believed could suit our needs and be downscaled appropriately, so our team took large inspiration from the DH-40 Twin rotary bender. This allowed us to have a general idea of how our model would work and give us insight on how to cut power requirements by making the technology more focused rather than being a universal bender.

E. Path to PDR (1.6)

While a large portion of the conceptual deign process has been completed there are still many components that need to be completed before a proper PDR can be completed. Firstly a cost and budget analysis must be completed to ensure that the Space Wire Bender would be effective in long term use of hastening and cheapening the cost of construction in space. A life style sustainment plan would also be needed to ensure that the device is properly maintained at a software level and that it is monitored for errors regularly so that if it needs manual intervention that can be completed before catastrophic failure. A plan for the full development, testing, and final evaluation must also be created so that an accurate timeline can be generated for the project's completion. To this end the necessary software required to make the device function would also need to start its development and have its requirements listed. A robust description of the attitude control system would be required as well due to the complex nature of the devices center of mass and its change moment of inertia due to the truss extending from the base. Lastly a method of securing the joints, as though the purely bent structures are strong they are also very flexible and without some method of securing the joints they will be much less efficient as structural elements.

F. System Engineering Milestones (2.5)

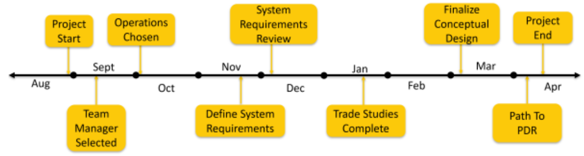


Figure 6: Timeline of milestone completion

The team completed most milestones in a timely manner though some were later than expected due to issues all tasks were still completed. Most difficulty came from trade studies which confusion arose in the team of what required trades and what didn't

VII. Conclusion

The team developed and assessed the concept and feasibility of an autonomous wire-bending system designed to fabricate stainless steel booms and trusses directly on a payload in space. We conducted trade studies on subsystem designs, which included the feeder, rotator, cutter, and bending head, to ensure precision, durability, and suitability for the harsh space environment. We integrated targeted mitigation strategies to address key challenges such as outgassing, thermal fluctuations, and debris exposure. The system was modeled in CAD and animated to visualize its operational sequence and demonstrate its capabilities.

The work marks a significant step toward enabling in-space manufacturing within future ISAM missions. The autonomous wire bender presents a scalable and feasible solution for the on-demand construction of critical structures, reducing dependency on pre-launched components and supporting adaptive fabrication in orbit. However, one of the current challenges is that the project remains conceptual because the team does not yet have access to the specialized equipment or facilities required to conduct the extensive testing for a flight-ready system. The following steps for moving this concept forward will require continued development, including physical prototyping, environmental testing, and payload integration, which are crucial milestones for transitioning from design to deployment.

VIII. Acknowledgements

Aerospace Corporations mentors Horace Lee and Antonella Pinola, and Senior Capstone advisor Michael Thorburn are gratefully recognized for their guidance in this project. COSMIC and C3 directors Jacob Rome and Joey Heying, alongside California State University, Los Angeles's Department of Mechanical Engineering, are also recognized for

allowing the opportunity for the authors to participate in this project.

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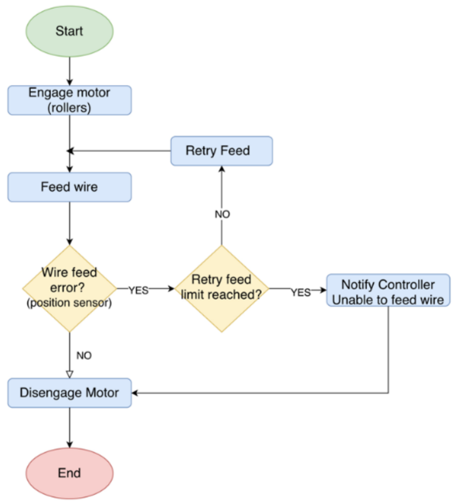
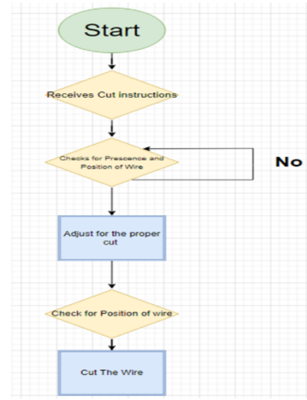
X. Appendices

Supplementary Material, Detailed Calculations,

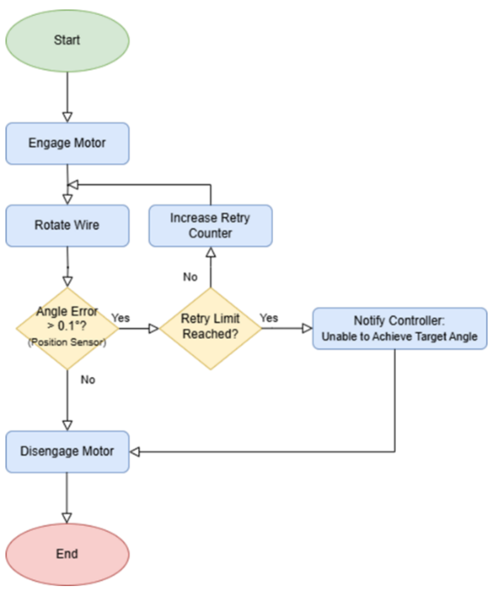
Additional Figures/Tables



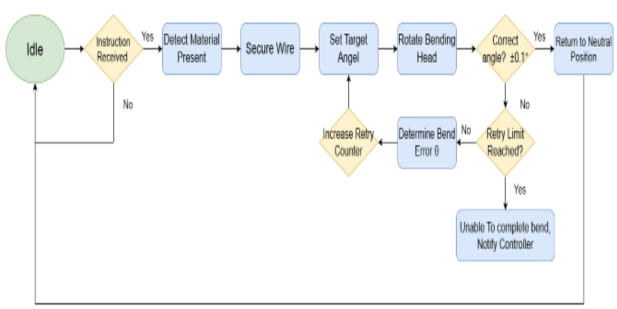
System Architecture: Feeder Flowchart



System Architecture: Cutter Flowchart



System Architecture: Rotator Flowchart



System Architecture: Bender Flowchart