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Cosmic Capstone Challenge – Aerospace Corporation

The Weldinator

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I. Abstract

As space exploration continues to advance, increasing efficiency in space operations is essential to reduce time and costs. The Weldinator project aims to develop a fully autonomous system capable of welding structural components in space, specifically for the preparation and construction of space-based infrastructures. Part of the motivation behind the Weldinator was to take the product from the Space Bender team and utilize the Weldinator to create structural elements like trusses. By utilizing an impulse laser welder, the system will precisely weld stainless-steel wire ends to enhance the rigidity of structures. The autonomous system employs advanced sensors, including LiDAR for spatial mapping and a vision sensor to assess weld quality. Clamps will be used to secure the wire in place before the welding process begins. This largely autonomous operation reduces the need for human involvement, enabling welding tasks to be completed without astronauts or their associated supplies. The Weldinator will operate within the harsh environment of space, relying on robust communication systems, such as a 922-FOM switch and 992-SFP optical transceiver, to facilitate remote operation. By minimizing human intervention, this system will strengthen spacecraft structures, improve longevity, and contribute to the safety and sustainability of future space missions.

II. Introduction/Problem Statement

The task of the project was to create a payload capable of completing a task autonomously, which could involve assembling, manufacturing, or repairing in space. It is to be hosted about the BCT X-Sat Venus Class bus that will have 3 or more operations. This payload's lifespan must be planned, and its systems must be defined for its intended purpose. The payload will focus on welding structural wires that serve as the foundation for creating structures in space. It will attach to the wires, analyze the area using sensors, and then weld the wires together. The sensors will verify the weld by ensuring there are no gaps along the welding area between the two wires.

III. Background Research

Spacecraft must endure an array of extreme environmental conditions as they operate in space. The design of spacecraft must account for challenges, ensuring longevity and functionality of the vehicle and its components. To commence this project, we start by researching the environment in which we are designing the spacecraft in. Designing instrumentation for on-earth use is completely different than designing it for in-space use. We must first comprehend the environmental factors that will affect our system and develop mitigations to overcome those challenges.

A. Environmental Factors in Space and Their Impact on Spacecraft Design

Space presents a unique and harsh environment that poses numerous challenges for spacecraft and their components. These challenges must be overcome when designing such instrumentation. These challenges include the vacuum of space, thermal cycling, charged particle radiation, ultraviolet radiation, and impacts from micro meteoroids and space debris. To overcome these obstacles, it is essential to use materials and design solutions that can withstand such factors. To gain a better understanding, we will go over some of the environmental factors in detail.

A.1 Environmental Factors in Space

- Vacuum: The vacuum of space causes outgassing to plastics and organic materials. Outgassing is the process in which a non-metallic material (Rubber, Adhesive, Polymers) will release gases when exposed to heat and/or a vacuum. The gas eventually condenses on other surrounding materials, potentially damaging sensitive equipment and rendering them inoperable.
- Thermal Cycling: Spacecraft experience extreme temperature variations due to the lack of atmospheric insulation. In space, temperatures can range from extremely hot to extremely come depending on whether the spacecraft is in direct sunlight or shadow. This cycling of temperatures stresses materials, which must be able to expand or contract without failing.
- Charged Particle/Ultraviolet Radiation: The lack of an atmosphere also means spacecraft are directly exposed to harmful ultraviolet (UV) radiation. This radiation can be harmful to sensitive electronics on the spacecraft and can degrade materials, especially plastics and other organic materials. This will weaken their structural integrity and performance over time.

- Micrometeoroids and Space Debris: There are space debris particles and micrometeoroids that when traveling at high speeds can cause significant damage. These space debris can travel at high velocities, averaging 10 km/sec.

A.2 Materials and Solutions

- Vacuum and Outgassing: To mitigate the effects of outgassing, there are a selection of materials that are durable and heat-resistant. High-strength alloys like aluminum, titanium, and stainless steel, are most used in spacecraft construction. These materials are chosen due to their strength-to-weight ratio, thermal performance, and resistance to corrosion.
- Thermal Control: Thermal control of spacecraft can be surface treated where an application of a coating or multi-layer insulation blanket is used. Surface treatment is required to prevent corrosion prior to launch. Multilayer Insulation blankets use multiple reflectors, usually thin polymer films with vapor-deposited metal on one or both sides. The films are fragile so a durable outer cover is added, and an inner cover may be added as well.
- Radiation Shielding: Now, current solutions to radiation shielding are limited and no definitive solutions to this problem for long-term manned missions exist. However, active shielding generated by either magnetic or electrostatic fields has been proposed.
- Micrometeoroid and Debris Impact: To protect spacecraft from high-velocity impacts of micrometeoroids and debris, engineers use Whipple shields. These Whipple shields consist of sacrificial bumper layers that absorb the energy of impacts.

Purpose, Scope, and System Context

The Weldinator is a semi-autonomous robotic platform designed for conducting structural welding operations in space, particularly aboard satellites and orbital structures. As communication plays a vital role in executing and monitoring these operations, the development of a detailed, technical storyboard was essential for both design validation and communication. It visually links function with architecture, establishing both the system's nominal behavior and its fault response capabilities.

Operational Initialization and Sensor Integration

A challenge that on-orbit manufacturing has is that it requires precision and live feedback. The full hardware configuration onboard the Weldinator, includes the xLink arm, 922-SFP optical transceiver, 922-FOM Ethernet switch, 922-DSL modem, 922-420 gateway, LiDAR, and a high-resolution camera. Then initialization of sensors as the system clamps into place and begins scanning its worksite.

In this stage, LiDAR and vision data are collected and analog environmental telemetry (temperature, force, and vibration) is routed through the 922-420 SIIS Gateway. The gateway converts these analog signals into Ethernet packets which are sent to the 922-FOM switch. This process enables real-time situational awareness and data prioritization. All digital signals from the sensors are streamed into the FOM, which acts as a central traffic controller.

Communication Transmission and Ground Station Feedback

An important part of the communications system is the critical loop of data transmission and feedback. Data will be routed from the 922-FOM switch to the 922-SFP optical transceiver. The transceiver converts Ethernet to optical pulses, which are transmitted to the optical laser terminal.

Once received by the relay satellite, the relay satellite will send the downlink to a ground station. Data is converted back into Ethernet format and analyzed on Earth. Mission operators review visuals, structural data, and system diagnostics in real-time. Now we get to the feedback control mechanism, where uplinked commands return through either optical or RF channels. The 922-FOM receives the uplink and forwards commands to relevant subsystems—adjusting the robot's position, triggering camera refocus, or reprogramming the weld path. This feedback loop is fundamental to maintaining precision and safety.

Failure Mitigation and Operational Continuity

Potential failures pose a risk and require appropriate mitigation measures. A possible issue is laser misalignment or environmental obstruction that disrupts the optical path. The 922-FOM detects the link degradation via onboard diagnostics and reroutes all data to the 922-DSL hybrid modem. RF signals are transmitted through a backup antenna to the same relay satellite.

Despite the communication fallback, mission continuity is preserved. The system seamlessly switches data channels without requiring manual intervention.

Another point of failure would be the electrical system having any type of fault limiting its power output to critical components like communication or welding system. An easy way to account for this would introduce redundancy in similarly critical components where space is available.

IV. Conceptual Design

The first step of the conceptual design segment was to produce ideas for what type of ISAM capability our system will be applicable too. The main idea the team supported was some type of welding. After selecting what the systems' capabilities and operations will be, research was done for each of the main options which are welding, movement mechanism, and sensors. Each operation had different proposals associated with them, so trade studies were conducted to determine the best overall option amongst the proposed ideas.

A. Movement Mechanism Trade Study

For the movement mechanism the proposed ideas were a Spider-Bot, Track Based mechanism, Robotic Arm, Snake or Worm like Robot, Cable Drawn mechanism, and a Free Flying System. The Results of the trade were:

Table 1. Movement Mechanism Trade Study Criteria

	Spider-bot	Track Based	Robotic Arm	Snake/Worm	Cable Drawn	Free Flying

Power	The number of legs increase the power needed	track design, number of motors, and surface interaction	More complex movement will require more power	surface interaction, movement complexity, actuators	Number of motors, cable length, and friction change power	Depending on the propulsion type the power can increase
Size	The size overall of the spider-bot will be less than a lot of the other options	The tracks will need to be preplaced or built while moving	Being able to retract will make more space for our system	The size would be smaller than a lot of the other options	the cable system would make this option larger as it adds more to the system	Wouldn't be a big system. Envisioned to be like the Astro bee
Longevity	wear on the legs	Wear from track and friction	depends on usage frequency and joint wear	Wear on all the moving parts with complex movement	Cable wear and motor strain	Thruster wear and power usage
Design	The spider design will add complicity as the number of legs matters	The track makes it more complex	extend/retract will add complexity but it is doable	More complex movement to mimic a snake or worm	The cable system makes it complex	The propulsion system is the entirety of the movement
TRL/Feasibility	TRL 5-6	TRL 1-3	TRL 7-9	TRL 3-5	TRL 5-6	TRL 5-7

After conducting a trade study on several types of movement mechanism ideas the one selection that had the most green and best Technology Readiness Level (TRL) was the Robotic arm. The Robotic Arm having a TRL of 7-9 indicates that this proposition is feasible meaning it is doable it also shows that Robotic arms are either being used in space missions or are being tested in space environments. In all the other categories in the trade studies the Robotic Arm has the greenest indicating that it is the best option in each section. While some of the other ideas had TRLs 1-6 with the lower the number being the less likely it is to be done as it has never been done before or it is in the initial stages of development. For example, the Track Based idea has a TRL of 1-3 meaning it is in initial stages of development. It was also red in most of its categories, meaning that in those sections that are red for the systems constraints this design would be more difficult and have more challenges.

B. Welding Trade Study

There are several forms of welding that will be investigated with those being MIG/TIG, Electronic beam, continuous and impulse laser welding. Factors that will be taken into consideration to choose a welding method is the operability within a vacuum, longevity of the component, power consumption, impact on the work piece/environment, operability within a vacuum and weight. These factors should allow for the most practical welding type to utilize when considering welding ¼ inch 316 stainless steel wires that will be used as framework for structures in space. Due to the environment being a vacuum it is important that the welding system can operate in such an environment. MIG/TIG/ laser welding all require the use of a shield gas due to the atmosphere interfering with the weld as it cools down. This is not a factor in space and so could be considered as a potential method. The only exemption in the welding methods listed would be the electron beam welder, which is typically used in vacuum chambers, and due to the environment allowing it to operate in a state that it is recommended for.

Longevity of the component refers to its ability to perform welds consistently without resupplying. For instance, MIG uses a consumable electrode during its welding process making it unacceptable for the application. As for other processes, they do not have any active consumption of materials to continuously weld. And due to the environment being vacuum no noble gas, which normally be a consumable for welds, allowing preservation of weight.

Impact of the work piece/environment can be from the slag caused by welds or local heating of the material due to energy inputted. TIG/MIG creates slag that can splatter around the work environment potentially causing issues with each weld. Electron beam welding has its precision with very minimal interference on the work piece. Continuous laser welding can heat up the work piece requiring it to cool off or the laser welder itself requiring time to cool off if temperatures reach a certain limit. Impulse laser welding is a brief operation that can specifically apply heat into a specific area preventing local heating. Constant use could also potentially lead to overheating. This could be managed with radiators allowing the heat to be dissipated through radiation.

Power consumption is a major topic as it should maintain a high rate of welds per hour. TIG/MIG uses an arc to melt the material. This process requires a lot of power and becomes unreasonable to be use with the given parameters for our MicroSat. Electron beam welding also requires a lot of power to perform its weld which can lead to either low welds per hour due to recharging, or its inability to perform the weld from insufficient power. Both continuous laser welding uses a constant beam of energy to heat the material and can drain power consumption, but with a constant influx of power from the solar panels it can be sustainable to melt the required amount of material. Impulse laser welding utilizes high peak power in a short amount of time allowing it to perform the weld given the constraints.

Table 2. Welding Trade Study Criteria

	TIG/MIG	**Electron Beam**	**Continuous Laser**	**Impulse Laser**
Longevity	MIG-consumable electrode	No known consumption of materials	No known consumption of materials	No known consumption of materials

Power Consumption	~3KW	High power consumption for electron emitter	Constant power consumption	Average, ~25W peak power output of 8.5KW
Heat	Excessively heats input	Minimal heat input	Continuous exposure could introduce excess heating	Local heating lasting in the milliseconds
Environment	Needs inert gas/vacuum	Normally operates in a vacuum chamber	Needs inert gas/vacuum	Needs inert gas/vacuum
Weight	MIG: 5-10 lbs TIG: 1-3lbs	A few pounds	Welding gun ~ 2-3 lbs	Welding gun ~2-5lbs

Plotting these attributes' characteristics will allow visual confirmation of the optimal welding method. For the circumstances given it will be Impulse laser that will be our main system to weld structural wire with.

C. Material Trade Study

Designing the system must fulfill certain constraints. Size, weight, and cost are among the most important criteria. For a system that is designed for in-space use, it must overcome the environmental factors. To overcome the environmental factors, it is important we evaluate and decide which material is best to be used for the system. Research concluded with three materials of choice, each with its unique properties and strengths.

B.1 Aluminum T6-6061

- versatile heat-treatable alloy
- tensile strength of 42 ksi, a yield strength of 35 ksi, and an elongation of 10%
- melting point ranges from 582 to 651.7 °C.

B.2 Aluminum 7075

- Average corrosion resistant material but has an extremely high fatigue resistance
- Compared to steel in terms of strength due to the high zinc content in its composition
- Ideal for highly stressed parts, such as fuselages
- Yield strength of 21 ksi when untreated and a Brinell hardness of less than 150

B.3 Aluminum-Lithium Alloy

Aluminum Lithium alloy is the most expensive among the three listed. This alloy offers a low density, high specific modulus, and excellent fatigue and cryogenic toughness properties. It has a melting point of 718°C, and its primary advantage lies in its weight. Making it highly attractive for applications where weight reduction is critical.

Evaluation

Each of these materials has its own set of advantages based on their alloy compositions. For instance, Aluminum 6061 is highly versatile, while Aluminum 7075 offers strength comparable to steel due to its zinc content. Aluminum-Lithium alloy, while extremely lightweight with superior toughness, comes at a higher cost.

This trade study has ranked the evaluation criteria in importance: Ease of Weldability, Material Cost, Strength, and Compatibility with Existing Systems. The ease of weldability was the highest-ranking factor, as the project revolves around an "in-space welder," and the ability to effectively weld materials in space is crucial. Material cost was also an important consideration, as engineering projects must be cost-effective. Strength was considered in relation to environmental factors to ensure the materials longevity in space. Lastly, compatibility with existing systems was evaluated, given that the machine is designed to weld aluminum for repairs on current spacecraft.

Based on these factors, it was concluded that Aluminum T6-6061 is the best material to choose. It is widely used in the aerospace industry.

D. System Stabilization Clamp Trade Study

The stabilization system must be capable of stabilizing the system by grabbing onto a quarter inch aluminum wire. This stabilization is crucial to ensure proper and efficient welds. Additionally, energy usage will be considered when researching different clamps or robotic arms. Specific rod dimensions are quarter-inch thick round stock.

D.1 Piston/Cylinder Driven Clamping System

- Operates using pressure to attract and retract the clamping arms
- Controlled by a pneumatic transmission powered by a pressurized air source
- Suitable for long-distance control

D.2 Worm Gear Driven Clamping System

- Powered by a small motor
- Uses a worm gear mechanism to attract and retract the clamping arms
- Operates with low energy consumption

Evaluation

The piston/cylinder setup, while capable of long-distance control, requires expensive and energy intensive technologies to operate properly. The pressurized chamber in the system is a critical component that must be kept under specific conditions, which could pose challenges in space were maintaining such a controlled environment is difficult. It adds unnecessary difficulties to the system.

In contrast, the worm gear driven clamping system has a simpler and more cost-effective setup. It requires minimal power from the main system and operates effectively with a compatible motor. The motor options for this system include a Brush D.C. Motor and a Brushless D.C. Motor. The Brush D.C motor has a limited lifespan of about 300 hours, whereas the Brushless D.C. motor lasts over 10,000 hours due to the absence of the brushes. Additionally, the Brushless D.C motor is compatible with solar arrays, lightweight, and commonly used in high RPM applications. It has already been successfully used in multiple space missions.

A primary concern for the worm gear systems is the friction generated by the worm gear. To mitigate this, a space-grade solid-based lubricant can be used, such as tungsten disulfide or molybdenum disulfide. These lubricants are resistant to outgassing and can withstand the harsh space environment. Another solution involves using materials with low coefficients of friction, such as bronze of NSM materials, to reduce friction between the gears. PTFE (Teflon), a material already used in space, is also resistant to space conditions and would be a suitable choice.

Given the evaluation of the systems, the Worm Gear Driven Clamp powered by a Brushless D.C. motor is the best choice. It offers greater efficiency, a longer lifespan, low power consumption, and is highly feasible for use in space.

E. Sensor Trade Study

To enable autonomous operation, Weldinator requires the ability to detect and map its surroundings. This will be achieved using a LiDAR sensor, which will generate a detailed spatial map. The map will interface with the robot's communication and control systems to determine navigation paths and clamping points for repositioning. Additionally, a vision sensor will be employed to assess the quality and integrity of each weld. This sensor will be strategically positioned to maintain a clear view of the welder arm during operation, ensuring accurate weld inspection.

LiDAR:

LiDAR operates by emitting pulsed laser light toward surrounding objects. The reflected signals are captured by a scanner, and the distance to each object is calculated using the time-of-flight data in conjunction with a GPS receiver. This enables the creation of a high-resolution 3D map of the environment. Due to its active remote sensing capability, LiDAR provides highly accurate spatial data. While the system demands substantial computing power and tends to be expensive, its proven reliability in space applications makes it a suitable choice. LiDAR is widely used in various fields, including aerospace, autonomous vehicles (e.g., Waymo), drones, mobile devices, and aircraft. Its GPS-based output is compatible with systems typically used in space navigation and mapping.

Vision Sensor:

The vision sensor captures visual data through an optical camera, converting light into electrical signals, which are then digitized and processed into usable images. The system isolates relevant information from these images to evaluate weld quality. For this project, we selected a SmartRay vision sensor equipped with integrated laser triangulation and JOSY software, enabling real-time, inline weld inspection. This capability is essential for maintaining weld quality and supports the autonomous functionality of Weldinator by providing immediate feedback on weld integrity.

Sensor Evaluation factors:

Sensor precision refers to the accuracy with which the sensor measures the scanning angle of detected objects, directly influencing the level of detail in the generated map. High precision, typically ranging from 0.05° to 0.2°, enables the creation of highly detailed maps capable of identifying small features and subtle object variations. Medium precision, between 0.2° and 0.5°, offers a balance between detail and performance but may miss finer details. Low precision, from 0.5° to 1.0°, results in a coarse mapping of the environment, with limited ability to capture smaller features. For Weldinator, high precision is required. An angular resolution in the range of 0.1° to 0.2° will ensure accurate environmental mapping and precise detection of structural elements, supporting both navigation and weld positioning in space. The output signal refers to the data generated after the sensor emits light pulses and calculates the distance and angle of detected objects. Higher output quality results in better resolution, which is critical for accurate weld analysis and quality assessment. For Weldinator, a minimum of 500,000 points per second is required to achieve the fine detail necessary for precision mapping. Sensor compatibility depends on the system architecture it integrates with. As LiDAR systems become more advanced, they often require additional components for data processing and operation, increasing overall system complexity. Sensor size is a key consideration due to strict space and weight limitations. For Weldinator, a compact and lightweight sensor is ideal, provided it still meets the necessary performance requirements for welding operations. Reliability is influenced by the sensor's ability to withstand harsh environmental conditions, particularly in space, and is also dependent on the quality of its internal components.

Table 3. LiDAR Trade Study

LiDAR Sensor	Small	Mid-Size	Large
Precision(Angular)	0.2 - 0.5	0.1 - 0.2	0.05 - 0.1
Space Environment	Moderate Tolerance	High Tolerance	High tolerance
Output Signal(pts/sec)	200k to 400k	500k to 1M	1M to 3M
Compatibility	High	Moderate	Poor
Size(cm, diameter)	5 to 10	10 to 20	20 to 40
Energy Usage(Watts)	5 to 15	20 to 40	50 to 100+
Cost (Dollars)	2k to 5k	5k to 15k	15k to 50k+
Life-Span(Years)	3 to 5	5 to 7	7 to 10
Range(Meters)	20 to 50	50 to 200	200 to 500
Speed(Hertz)	10 to 15	15 to 20	20 to 30
Reliability	Moderate	High	High
Resolution(Channels)	16 to 32	32 to 64	64 to 128+
Autonomous	Limited	Moderate	High
	CHOSEN		

Table 4. Vision Sensor Trade Study

Vision Sensor(Camera)	Small	Mid-Size	Large
Precision(Angular)	0.5 - 1	0.2 - 0.5	0.05 - 0.2
Space Environment	Fair Tolerance	High Tolerance	High Tolerance
Output Signal(MB/sec)	10 to 50	50 - 200	200 - 500
Compatibility	High	Moderate	Poor
Size(cm, diameter)	3 to 8	8 to 15	15 to 30
Energy Usage(Watts)	1 to 5	8 to 15	15 to 50
Cost (Dollars)	500 to 3K	3K to 10K	10k to over 50k
Life-Span(Years)	2 to 4	4 to 7	7 to 10+
Range(Meters)	1 to 10	10 to 50	50 to 200+
Speed(FPS)	15 to 30	30 to 60	60 to 120+
Reliability	Moderate	High	High
Resolution(Pixels)	640x480x1280x720	1280x720x1920x1080	1920x1080-4K+
Autonomous	Limited	Moderate	High
		Chosen	

These trade studies compared small, mid-size, and large sensors to evaluate how physical space constraints impact sensor selection. While smaller sensors are preferred due to limited available space, the analysis focused on understanding the trade-offs—larger sensors typically offer improved performance but require more space and power. Identifying the optimal sensor size depends on balancing system capabilities with performance needs. Ultimately, selecting the right sensor for the Weldinator requires a clear understanding of both its operational requirements and acceptable compromises. Mid-size LiDAR and vision sensors were selected as they offer an optimal balance between physical size and performance, aligning with the Weldinator's operational requirements for in-space functionality.

F. Communications and Data Collection

The Weldinator project is a semi-autonomous robotic welding platform designed for on-orbit satellite and spacecraft repair missions. Operating in Low Earth Orbit (LEO), the Weldinator must maintain reliable, high-throughput communications between its onboard sensors and actuators, a relay satellite, and a ground control station. To accomplish this, the communication architecture is built upon a dual-path system combining free-space optical links for high-speed transmission and RF pathways as a resilient fallback.

The primary communication components consist of Moog's 922-series industrial hardware: the 922-FOM Ethernet Switch, 922-SFP Optical Transceiver, 922-DSL Hybrid Modem, and 922-420 SIIS Gateway. These modules support signal conversion, data routing, and transmission across optical and RF channels. Their configuration ensures that data integrity, command responsiveness, and operational redundancy are preserved under the demanding conditions of space.

Data Acquisition and Signal Flow

Data collection begins at the sensory interface. The Weldinator is equipped with a Smart Ray Eco camera for high-definition visual input and LiDAR sensors for spatial mapping and weld positioning. Additional analog sensors (e.g., for temperature, force, or current monitoring) are connected to the 922-420 SIIS Gateway, which converts analog 4–20 mA signals to digital Ethernet (100Base-TX).

The 922-420 communicates with the 922-FOM Ethernet Switch, which serves as the primary data hub onboard. Digital signals from the camera, LiDAR, and sensor gateway are routed through the 922-FOM and prioritized based on mission parameters. For instance, real-time LiDAR data required for weld path tracking is transmitted with higher priority than periodic telemetry logs.

Data from the 922-FOM is then directed to the 922-SFP Optical Transceiver, which encodes the Ethernet packets into optical signals. These signals are passed to the optical laser terminal for free-space transmission to a relay satellite in orbit. When a communication fault or misalignment occurs in the optical pathway, the 922-FOM reroutes the data to the 922-DSL Hybrid Modem. The modem transmits via Ka/X-band RF channels, ensuring continued operation.

Transmission, Ground Link, and System Integration

Upon reaching the relay satellite, optical or RF signals are downlinked to the ground station. The ground station outfitted with both optical receivers and RF antennas, converts the signals back into Ethernet format. From there, ground control systems parse, log, and analyze incoming data using high-performance computing platforms. Control signals generated by operators or autonomous ground-side software are uplinked via the same satellite, either optically or through

RF, and received by the 922-FOM. These are routed to the appropriate subsystems onboard: control commands adjust welding parameters, camera orientation, LiDAR sweep angles, or initiate safety shutdowns.

Each communication component is powered via a +24V DC power bus, stepped down with dedicated DC-DC converters. The estimated total system power draw is 20–25W. The system includes fused protection for each communication module and thermal insulation to withstand the LEO environment. Optical data paths are encrypted using AES-level security, and the switch includes watchdog monitoring for fault detection.

In total, this integrated system ensures real-time data collection, secure transmission, and responsive control—making it fundamental to the autonomous functionality and mission success of the Weldinator.

Communication Trade Study — Optical vs. RF

The Weldinator communication system was developed through a trade study comparing two primary modalities: free-space optical communication and radio frequency (RF) transmission. This analysis weighed performance against mission constraints, environmental limitations, and system-level risks.

	Radio Frequency (RF) Communication	Optical (Laser) Communication
Longevity	Extensive track record in space applications since 1950	A newer technology, it has only been around for about 30 or so years but so far is functional and has improved
Power Consumption	S-band transmitters (commonly used in space applications) may consume anywhere from 5 to 30 watts for typical transmission scenarios.	Optical systems, due to their need for high-power lasers and sensitive receivers, can consume significantly more power. 20 to 100+ watts, depending on the complexity and capability of the system.
Data Rate	**200mbps**	**1.2 gbps**
Integration	Relatively straightforward due to the mature technology and the wide availability of space-qualified RF components. Antenna pointing requirements are less stringent than for optical systems.	Includes a laser transmitter, an optical (photonic) receiver, optical modulators, and telescopes or optical antennas. These systems require precise alignment and stabilization to ensure the laser beam accurately targets the receiver, which can be challenging on a moving platform.
Interference	More prone to sound and other RF frequency interference	Optical signals are immune to RF interference, offering cleaner data transmission.
Latency	Both technologies use electromagnetic waves that travel at the speed of light, so the latency is primarily determined by the distance between the transmitter and receiver.	Both technologies use electromagnetic waves that travel at the speed of light, so the latency is primarily determined by the distance between the transmitter and receiver.
Relay or DTE (Direct to Earth)	for deep space missions due to the limited power and range of onboard transmitters. Relay satellites amplify the signals and help maintain communication with Earth. While for direct communication is possible for missions closer to Earth, such as in low Earth orbit (LEO), where the distances are shorter, and direct line-of-sight communication is feasible.	While optical systems can offer direct communication with very high data rates over long distances, they benefit significantly from relay satellites, especially in handling issues like Earth's atmospheric interference and providing broader coverage.
TRL/ Feasibility	**TRL 9 is already currently used in space missions for over 50 years**	**TRL7-9 has been implemented in missions since 2001 but hasn't replaced RF communication entirely and requires significantly more power**

Conclusion of Trade Study and Implementation Justification

The dual-mode communication system integrates the advantages of both optical and RF pathways. The optical system is designated as the primary channel due to its superior throughput and signal integrity. RF serves as a fallback mechanism, providing redundancy for mission-critical functions. The Moog 922-SFP was selected for optical transmission based on its compatibility with existing industrial networking standards and its small form factor suitable for space-rated integration. The 922-DSL modem was chosen for its multiprotocol capabilities and robustness in challenging environments.

In combining these technologies, the Weldinator achieves a balance of performance, redundancy, and system-level fault tolerance. The trade study guided this architecture to ensure mission continuity, data availability, and flexible control under both nominal and degraded conditions. This approach is representative of best practices in satellite communication design and supports long-term autonomy and resilience in on-orbit robotic maintenance operations.

V. Detailed Design

A. System

After reviewing all the trade studies all the items that were selected became part of the system. Each of the components has their own functions but synchronize to make the system itself function. How the system will work is firstly it will start then the clamps and arm will be on standby. Secondly, the sensors will scan for wire using the Lidar sensor. Next, the sensor will acquire the distance and relay the information to the arm and clamps. The Clamps will move towards the location and clamp down and the arm will move towards the location and be on standby. The welder will then weld at the location and all the components will wait for further instructions from the sensor letting them know whether to move to another location or wait until the weld is sufficient. Finally, when there are no more welding locations the sensors will relay that information to the components to go back to a neutral position and stop.

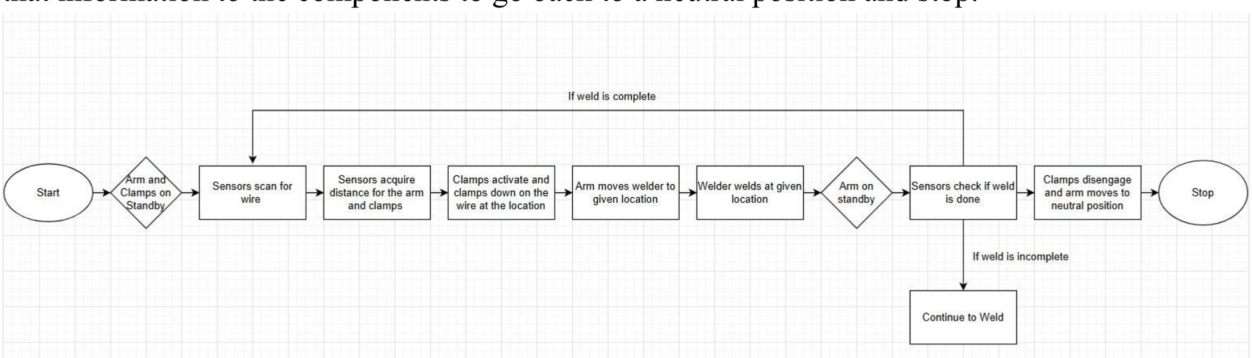

Figure 1: System Flow Chart

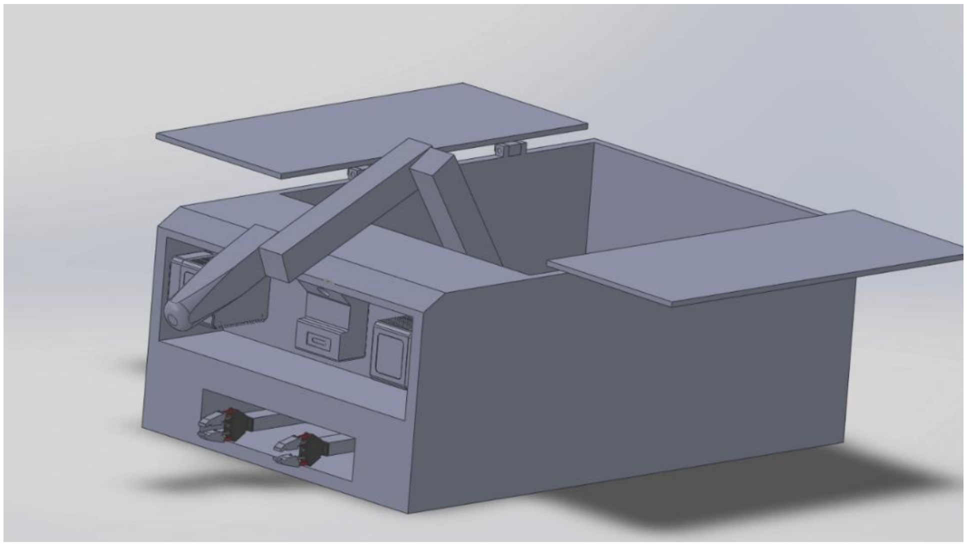

Figure 2: SolidWorks model of the system with all components

B. Impulse laser welder

After choosing laser impulse welding as our main source of welding. Technical specifications are required based on material parameters and dimensions of the weld. For this instance, the weld will penetrate 5/64th of an inch or 2mm from the surface. Taking the depth and spot weld diameter of 2mm. The total energy needed would be the energy required to raise the temperature to its melting point, and the energy needed to make the transition from solid to liquid.

$$Q_{Melt} = mC_p\Delta T \ (Ref.[1])$$

$$Q_{Lm} = L_{mf} \cdot m \ (Ref.[2])$$

By using equation [2] and [3] we can create equation [4], and since the mass that is heated is unknown. It can be derived from what is known which will be the density as well as the volume to get our final equation [5].

$$Q = (\rho v)C_p\Delta T + L_{mf} \cdot \rho v \ (Ref.[5])$$

$$Q = 16.99J$$

M = Mass
V = Volume
D = Pulse duration
ρ=Density of 316 stainless steel
T=Temperature
Q = energy

Cp = specific heat capacity

And using settings that are present in current YAG impulse laser welders with an energy input of 17J at a time span of 2 milliseconds. It was calculated that the necessary peak power level being 8.5 KW.

The operational breakdown of the welding system is shown in Fig. (3), where each step is depicted. The major steps include verifying a stable attachment to the workpiece, checking if enough power is stored before the welding process begins, and checking the completion of the weld. Once the welds are completed and the unit is ready for relocation, the welding arm will retract until its deployment is needed.

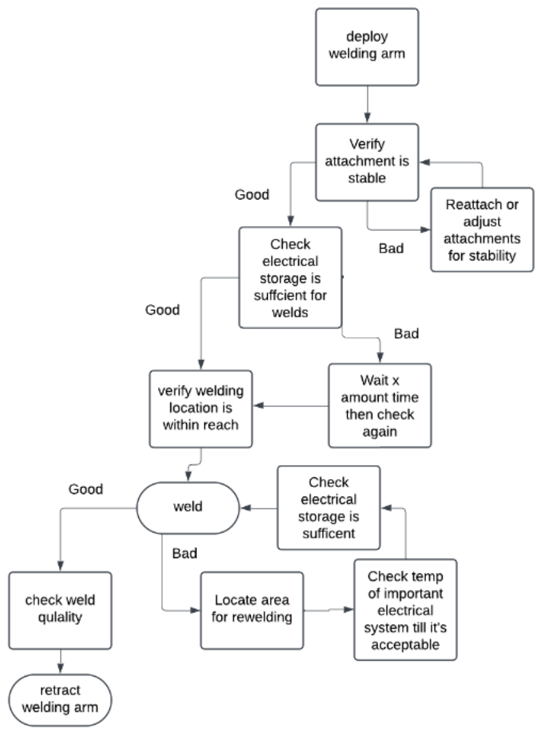

Figure 3: Welding system flow chart

C. Robotic Arm

Since selecting the Robotic Arm as our movement mechanism for our system, identifying the specifications of an arm that would fit the project's constraints was the next goal. Before doing this deciding on a method to choose how to pick an arm was a challenge. The main methods were either downsizing existing robotic arms in space missions, space qualifying a commercially available robotic arm, or finding an arm that fits the project's constraints. Fortunately, after researching many robotic arms either commercially available ones or utilized in space missions, the chosen method was to find a Robotic Arm that is already space qualified and met the constraints. The arm that was chosen for the systems' movement mechanism was Motivss's xLink Space-Rated Modular Arm System.

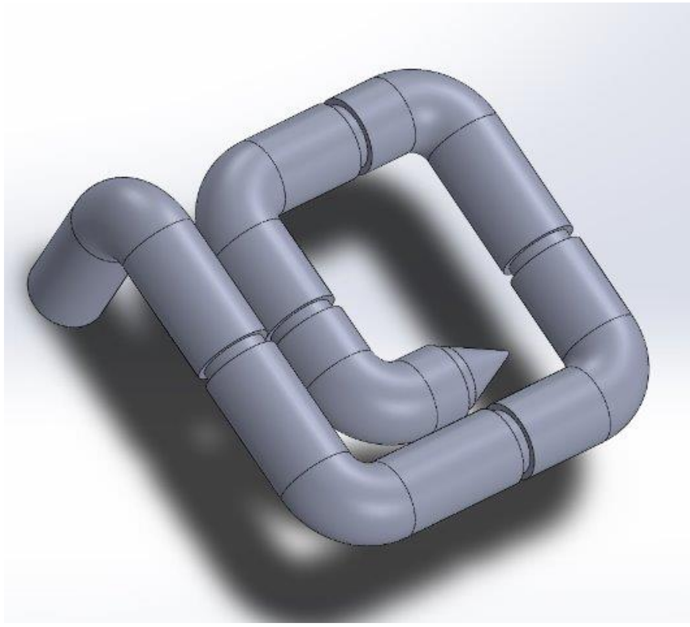

Figure 4: SolidWorks model of arm rotated inward has a volume of 15.82687 in x 15.19268 in x 8.505929 in (when fully extended has a reach of 35.92584 in)

According to Motivss the baseline model of the xLink Space-Rated Modular Arm System has a mass of around 22kg, a six degree of freedom configuration, power consumption ranging from 125 to 150 Watts. It is also scalable meaning that the baseline model can be adjusted to the project's constraints. The xLink arm is being used on NASA's OSAM-2 mission so proving the scalability of this arm.

After defining the specifications of the arm, the next goal is creating how the system will operate. The arm consumes from 125 to 150 W so when the arm is not in operation or idling the power to the arm will either be suppressed or dampened. The main story about the life of the arms operation will be first power gets sent to the arm and turns on. Secondly it will unfold and await instructions from the sensors. Third it will move towards the location given by the sensors. Fourth it will remain idle during this stage power will be completely cut off or only a little bit will be sent to the arm. Fifth it will receive information from the sensors again letting the arm know if stays for a reweld, move to another welding location, or if there are no more welding locations left. Sixth when there are no more welds to be done the arm will move back to its initial compact position. Finally, the power to the arm will shut off stopping the arm.

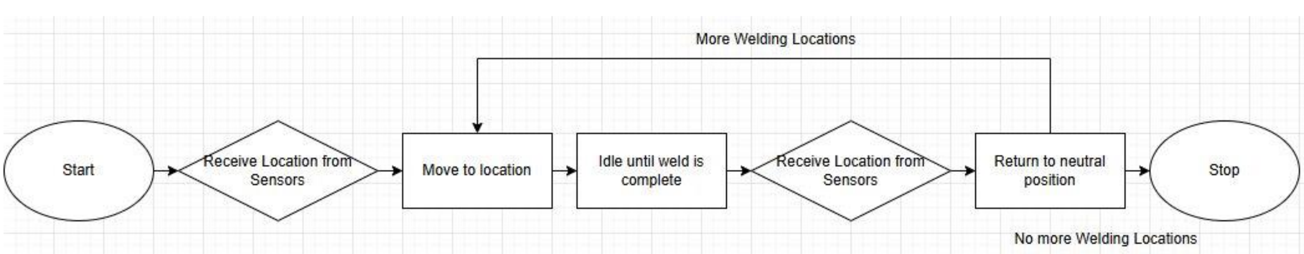

Figure 5: Robotic Arm Flow Chart

The biggest concern or risk of the arm is wear since the Robotic arm has several moving parts that move. Another risk is loss of power to Actuators. The effects of these risks can result in the failure of joints and actuators, loss of lubrication, and loss of synchronization with other components in the system. To mitigate these risks, the system should include backup power systems and make good lubrication on high friction components.

D. Stabilization Clamps

Selecting the worm gear driven clamping system does not require an expensive set-up to operate properly. All it will need is material that is compatible with the environment of space. The system will consume little power from the main system. The system requires a motor to operate properly. The Brushless D.C. motor is solar array compatible, is light weight, and is used during high rpm applications. The Brushless D.C. motor has already been used in space for multiple missions. It uses up to 1 Watt or up to ½ horsepower.

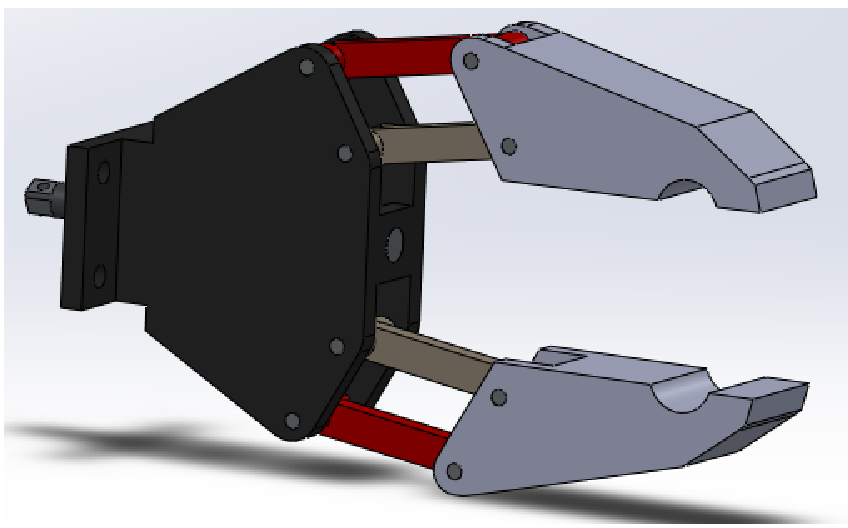

Figure 6: SolidWorks Model of the worm gear driven stabilization clamp

The worm gear's greatest concern is the friction the worm gear will create. To overcome this challenge, we can include a space grade solid-based lubricant. For moving mechanical assemblies exposed to space environments, tungsten disulfide or molybdenum disulfide are options to explore. Bonded solid lubricants may be a resin binder or inorganic binder that is resistant to outgassing. Vacuum compatible grease to lubricate gears and moving mechanical components include molybdenum disulfide additive.

The worm gear can also be made of a material with a low coefficient of friction to overcome the challenge. Materials like bronze and NSM materials have low coefficient of friction. Material like PTFE (Teflon) is already widely used in space and is resistant to the harsh environment in space.

This chosen technology will be driven by a Brushless D.C. motor due to their efficiency, long lasting lifetime, low power consumption, and feasibility in space. The weight for the clamp will be about 12 kg and will consume about 1-5 Watts when in use. The clamp will work as follows, it will stand-by and await instructions. It will then check for presence of the wire and will adjust the system for a proper clamp. It will check for the position of the wire, if it is clampable then it will drive the clamps to stabilize the system. If the wire is not in position, then the system will adjust until it is ready for a proper clamp.

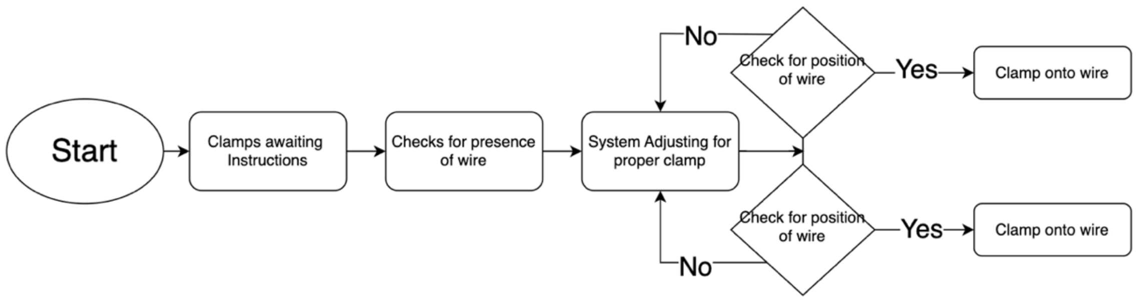

Figure 7: Stabilization Clamp Flow Chart

VI. Conclusion

The Weldinator was created to complete an ISAM capability, and it falls under the Manufacturing segment. This system adheres to the project's dual solar array constraints. The payload will weld structural wires that will be used to create rigid structural elements like trusses. This system can also work alongside the Space Bender payload as that system's output is bent wires. With all the chosen mechanisms they will work cohesively together ensuring the system's functionality. The Weldinator will operate in the harsh environment of space and work through all the environmental challenges. The Weldinator addresses the project's mission of having a payload capable of completing a task and having three or more operations.

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VIII. Appendix

Category	Risks	Damage/Effect	Mitigation
Environmental	Radiation	Electronics/ Degradation of Materials	Multi-layer Insulation/ Shielding/ Rad-hard chips
	Heat	Thermal Expansions/ Material Deformation/ Overheating of circuits	Multi-layer Insulation
	Space Debris(minimal dmg)	Hull penetration/ Damaged internals	Shielding
Sensors	Electrical Failure	Loss of Functionality/ Inaccuracy	Space qualify(Rad-hard components, Thermal management)
	Connection to comms	Inability to transmit Data/ Synchronization with other systems	Redundant comms system/ Autonomous Data Storage
Clamps	Continuous Motion	Performance/ Wear/ Fatigue	Material Selection/ Redundant fasteners
	Lubrication/ High friction coefficient	System malfunction/ outgassing/ Wear/ Increased Energy consumption	Space grade lubricants/ use material with low friction coefficient
Welder	Failure in Capacitors	Limits power output/ ineffective welds	Space qualified capacitors/ backup power systems/ Solid state components
	Overdraw of repetitive power	Heating of critical components/ electrical system failure	Power management/ energy efficient design/ load shedding
Arm	Wear/ Fatigue	Failure of joints and actuators/ loss of lubrication	Low friction coatings
	Power System Failure/ Loss of power to actuators	Inoperability/ loss of Synchronization with other systems	Backup power systems/ Redundant actuators/ Energy management
Communications	Corrupted Data	Loss of communication/ reduced system efficiency	Redundant channels
	Signal Noise	Reduced communication range/ Degraded signal quality	Signal filtering/ Frequency hopping

Risk and Mitigation Matrix

SolidWorks Model of fully extended xLink arm (reach of 35.92584 in)

$$Q = \left(7980\,\frac{kg}{m^3}\cdot 2x10^{-9}m^3\right)\cdot 490\,\frac{J}{kg\cdot K}(1645K - 2.7K) + 260\,\frac{kJ}{kg}\left(7980\,\frac{kg}{m^3}\cdot 2x10^{-9}m^3\right)$$