RADFAB ConOps

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1. **Introduction**

1.1 Project Description

1.1.1. Background

In the current environment of spacecraft and satellites development there exists a need to develop in-space servicing, assembly and manufacturing (ISAM) technologies to enable further advancement of spacecraft capabilities and space economies. Currently, no integrated assembly and manufacturing ISAM options exist which can perform structural assembly, array fabrication and electrical wiring in one system. The proposed system, RADFAB, can perform all these operations in one robotic system, reducing overall cost. A low-cost, highly capable ISAM system would significantly reduce the cost and alleviate launch constraints imposed upon large satellite and station missions. This will be accomplished by the removal of launch force survival criteria, launch vessel size limitations, deployable mechanism reliability and electrical wiring adhesives.

1.1.2. Assumptions and Constraints

The RADFAB concept makes the assumptions that the following technologies will be matured by the system's development timeline:

- Resonance-Assisted Deposition manufacturing (Currently TRL 4)
- Solid-State Ceramic Coating manufacturing (Currently TRL 2)
- Autonomous robotic assembly in space (Currently TRL 2)

1.2 Overview of the Envisioned System

1.2.1. Overview

RADFAB is a multifunction robotic ISAM system capable of assembling functional spacecraft and satellites from flat-packed components delivered in any traditional launch vehicle. RADFAB utilizes Resonance-Assisted Deposition (RAD) technology, a solid-state wire-bonding process as its primary construction method. The system consists of a SCARA robotic arm holding the RAD and SSCC tool, a linear rail for large x-movement, and a series of linear screw motors for large z-movements. Limited alumina powder feedstock will be stored in the SSCC alumina feeder, with most of the feedstock being stored on the product structure as it is assembled. A docking interface (see section 3.3) will be required on each part to allow RADFAB to secure and orient it properly, as well as for RADFAB to traverse the existing structure.

1.2.2. System Scope

Whilst a mature RADFAB robotic system is scalable in concept, the linchpin technologies have yet to be proved adequate, notably orbital RAD application and the SSCC process. As such, the C3-RADFAB mission will have a simplified control system, with the overall mission aimed at demonstrating the technological readiness of the mature RADFAB processes. The C3-RADFAB system will operate wholly within the dual solar array BCT X-Sat Venus Bus. C3-RADFAB will utilize 24 AWG aluminium wire for structural and electrical connections. The robotic system will require optical, IR, pressure, and conductivity sensors for data acquisition, clearly defined data on the type of parts and their proper assembled form that it will be given, power and a high-frequency AC signal to function.

The project will cover the development of a technological demonstration unit of the RADFAB system up to the design of the demonstration cell, analysis and requirements studies for the whole robotic system, the full development of the RAD and SSCC toolheads, feedstock storage systems and data analysis from the experiment. Development of robotic pathfinding and assembly software and the high-frequency AC signal generator. The satellite bus for this experiment will be outsourced to Blue Canyon Technology which will be providing a Venus-class satellite bus.

2. Documents

2.1 Applicable Documents

C3-RADFAB Design Reference Mission

IoMOS DRM

Presentation Document

Trade Studies Document

2.2 Reference Documents

[1]

A. Deshpande and K. Hsu, "Acoustoplastic metal direct-write: Towards solid aluminum 3D printing in ambient conditions," *Additive Manufacturing*, vol. 19, pp. 73–80, Jan. 2018, doi: https://doi.org/10.1016/j.addma.2017.11.006.

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A. Deshpande, A. Tofangchi, and K. Hsu, "In-process Microstructure Tuning in Solid-State Ambient Condition Metal Direct Manufacturing," *Procedia Manufacturing*, vol. 34, pp. 678–682, Jan. 2019, doi: https://doi.org/10.1016/j.promfg.2019.06.196.

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NASA, NASA Systems Engineering Handbook, rev. 2. Washington, D.C.: National Aeronautics and Space Administration, 2007. [Online]. Available: https://www.nasa.gov/wp-content/uploads/2018/09/nasa_systems_engineering_handbook_0.pdf.

[4]

B. Langenecker, "Effects of Ultrasound on Deformation Characteristics of Metals," in *IEEE Transactions on Sonics and Ultrasonics*, vol. 13, no. 1, pp. 1-8, March 1966, doi: 10.1109/T-SU.1966.29367.

3. Description of Envisioned System

3.1 Needs, Goals, and Objectives of Envisioned System

RADFAB needs to be able to demonstrate the welding of two solar cells creating a solar array. One solar cell will be fixed and the other positioned by RADFAB to lay aluminium traces. Our objective is to showcase the potential of autonomous assembly in space for large solar arrays.

RADFAB will deposit aluminium traces on the solar array with an insulating ceramic coating. The insulated wire after being welded will be connected to an electrical conductivity sensor, which would then be leveraged to conduct illumination, series, string and parallel solar array tests. We aim to showcase a positive connection between the solar array via the solar cell traces and alumina coated wire.

RADFAB needs to demonstrate the aluminium welding of two girders. To demonstrate this capability RADFAB will position a tensile test coupon in a tensile tester. The placed coupon and static coupon will then be welded together. Following a successful weld alumina coated wire will be laid across the weld seam to demonstrate the ability to lay wiring across aluminium structures. Following this, the tester will apply tensile stress to the coupons to evaluate the strength of the weld joint.

3.2 RAD Method

The consolidation of solar cells, aluminium traces with ceramic coatings, and tensile joining is achieved through the Resonance-Assisted Deposition (RAD) method. The RAD method uses piezoelectric discs that are exited through voltage input causing them to expand and contract. This feature allows the transformation from ultrasound to be converted into mechanical energy. Hence the tool will begin to vibrate in an oscillatory manner at frequencies of 40 to 60KHz but not limited to.

When these oscillations are applied directly to a material it causes vibrations to propagate, reducing the materials static stresses and bringing it into acoustic softening. When static compression is combined with resonance the material sees shear oscillatory movement causing the atoms to move and consolidate. This combined in a step wise method can create voxels and these voxels will create lines, and the lines can create layers when stacked together. It is worth noting that the RAD method can work utilizing no heat source which makes it an energy efficient (<200 Watts of power consumption) metal additive manufacturing.

Additionally, once the ultrasound is deactivated the material experiences acoustic hardening due to the equiaxed grains in the material hardening the metal crystals. Acoustic energy, much like heat, can facilitate atomic movement and dislocation; however, it is preferable because it induces localized grain structure refinement rather than widespread thermal convection [4].

3.3 Overview of Key Systems and Elements

3.3.1. RMS

The primary motion system of the RADFAB system is consolidated into a single assembly, referred to as the RAD Motion System (RMS), which can be positioned relatively close to the workpieces by moving the robot, or in the case of C3-RADFAB, the gantry system. The RMS comprises of two main components, a gripper to secure and hold components, and an independently movable SCARA arm with the RAD and SSCC tools as the end-effector. By moving the whole unit, the piece can be positioned relative to another fixture or workpiece to allow for RAD bonding, or a chip can be held for wiring traces to be laid down. Overall, the RMS is capable of 4 axes of motion and utilizes 4 motors to perform this task. All motors are in a direct-drive configuration to increase reliability and save weight.

3.3.2. X-Axis ball screw

The secondary motion system of the proposed robotic manufacturing system is composed of two components. The first of which is an x-axis ball screw. The x-axis ball screw moves the entire RMS system along the x-axis allowing for movement of the pick and place tool as well as preforming fast and large x-axis movements. The axis is composed of a single off-the-shelf NEMA-17 stepper motor fixed to a ball-screw linear rail.

3.3.3. Z-Axis Linear Motion System

The second component of the secondary motion system is the z-axis bed motion system. The z-axis motion is accomplished by assembling four linear ball-screws and 4 NEMA-17 (X) stepper motors fixed to four guide rails. All components of the z-axis linear motion system off-the-shelf space heritage components.

3.3.4. RAD Tool

The RAD tool consists of two piezoelectric discs stacked in parallel. These discs are configured to resonate at 60 kHz, although the system is not limited to this frequency. The discs are torqued to activate the piezoelectric crystals, and when a voltage is applied, they contract and expand, converting electrical energy into mechanical motion.

When the system resonates at the discs' natural frequency, the piezoelectric elements oscillate, transmitting energy into the horn section. This horn holds a diamond-coated tungsten carbide tool, which also resonates at the same frequency. The tool is specifically designed with chamfers to avoid cutting the wire during operation. Instead, it generates shear stresses on the wire and substrate through resonance and static compression.

As previously described, this technology enables mass transport via resonant energy. The shear forces produced help move material and combined with compression, allow energy to couple into the substrate. This results in the consolidation of feedstock into voxels, which are then joined into lines. These lines are subsequently stacked and bonded together to form the final structure.

3.3.5. SSCC Tool

The SSCC tool uses a derivative of the RAD process to coat wire uniformly in RAD-compatible powder materials. C3-RADFAB uses this tool to coat wires in alumina, electrically insulating them for bonding to conductive structures and in areas of potential electrical interference. The SSCC tool can be used in-line with the RAD process, coating wire and then feeding it to the RAD tool for printing.

3.3.6. Powder Hopper

A powder auger is used to feed alumina powder to the SSCC tool. This powder auger uses transducers to vibrate the alumina powder, allowing it to flow easily in a fluid state. The powder is stored in the auger's piston assembly itself, containing all the powder needed for C3-RADFAB's mission, in addition to a safety factor.

3.3.7. Solar-Cell Tester

The solar cell tester is the primary method to evaluate test build 2, a trace-laid and RAD bonded miniature solar array. The tester features one half of the specimen already mounted, with the other half stored on a tray, being held down with spring clips. During the test build operation, the RMS will move half of the test build to the solar cell tester and bring them in alignment. Then the solar cells will be RAD welded together, following a successful RAD bonding of the solar panels, wire traces will be laid across the solar cell. Following completion of the test build operation a UV light will be activated, and a series of standard solar cell tests will be run to evaluate test-build quality.

3.3.8. Tensile Tester

The tensile tester is the primary method of evaluating test build 1, an aluminium tensile specimen. The tester features one half of the specimen already mounted, with the other half stored on a tray with spring clips holding it down. During the test build operation, the RMS will move half the specimen from the tray into alignment with the other half and bond them together. Spring clips will hold the specimen in place when properly positioned. A motor-driven ball screw stage will be used to apply tension to the sample for tensile and fatigue tests, which will be measured by a strain gauge.

3.3.9. Optical Camera

The optical camera is a tertiary system for evaluating test build 1 and test build 2 as well as a vital system for troubleshooting. The optical camera will allow ground control to evaluate test piece placement, tool position, weld quality, damage assessment and document RADFAB operation for further missions and system improvements.

3.3.10. High Data Rate Transmitter

The high data rate transmitter is a fundamental component of RADFAB's communication system, designed to encode and modulate data for transmission to ground stations. It converts digital data into a high-frequency radio signal, facilitating data transfer. Additionally, it supports the reception and demodulation of incoming signals, enabling telemetry, telecommand, and data downlink functions. To fill this vital role a space heritage high data rate transmitter will be procured from ISISPACE.

3.3.11. Omnidirectional Antennas

RADFAB utilizes omnidirectional antennas to ensure constant communication with ground control, regardless of orientation. Additionally, the high number of omnidirectional antennas provide ample redundancy in the event of an antenna failure. Ensuring a partial communications failure does not necessitate the termination of the mission. To achieve this off-the-shelf space heritage omnidirectional antennas will be procured from ISISPACE.

3.3.12. Waveform Generator

A custom-made space hardened waveform generator will generate the ultrasonic frequency needed to perform the RAD and SSC process. This generator will operate on 24V and create a tuneable output frequency between 40-70kHz. This waveform generator will be custom ordered to meet the requirements for the RAD process and to survive the space environment.

3.3.13. CNC Control Board

The robotic motion system will be controlled utilizing a radiation hardened Duet 3D MB6HC. The Duet board will receive commands issued from the SBC and send signals to drive the various stepper motors and servos on the RADFAB, as well as monitor and transmit sensor data to the SBC. The Duet MB6HC board also has the capability to quickly flash new versions of firmware, allowing for software fixes to be quickly implemented in the case of a software failure.

3.3.14. SBC

An off-the-shelf space-rated Raspberry PI, Astro PI, to bear the primary computational load of our RADFAB system. The Astro Pi will interface with our waveform generator, transmitter board, motion electronics systems and sensors. Data will be logged to solid-state storage mounted to the Astro Pi. A modified Linux-based operating system (Alpine Linux) will be used for power efficiency and in-process upgrading of system software.

3.3.15. Internal Battery

The internal battery provides electrical storage to supplement the BCT-X's internal 10.3Ah battery, allowing for extended operation whilst not in direct sunlight. Additionally, this enhanced storage capacity allows for relatively short, high voltage discharges that would otherwise not be possible. For example, the high voltage needed to power the ultrasonic waveform generator. This supplemental internal battery will be rated for 30Ah at a discharge voltage of 24V. The battery will be custom ordered from a satellite battery supplier.

3.3.16. Power Supply

The power supply is responsible for all AD to DC, voltage and current conversion conversions in the electrical system. Ensuring proper powering of each electrical component at correct voltage. Additionally, the power supply is responsible for routing excess generated electricity to the BCT-X and supplemental internal batteries, storing power gathered during windows of low-activity in direct sunlight.

3.4 Interfaces

3.4.1. Power

- MIL-DTL-32139
- MIL-DTL-3899
- PC104
- 2.54mm pin connectors
- USB-C

3.4.2. Tensile Bar

- Spring-loaded clips hold dynamic tensile bar

3.4.3. Solar arrays

- Spring-loaded clips hold dynamic solar cell

3.5 Modes of Operations

- Active printing mode
  - **See section 6.1.2**
- System Hibernation
  - Disable all systems except for SBC, data transmitter and downlink antennas
- Testing mode
  - **See section 6.1.2**
- Diagnostic Mode
  - Full-power uplink & downlink
  - High-voltage power systems default off
  - Actively sending & receiving system data and software commands to/from ground station

3.6 Proposed Capabilities

- Positioning and joining structural components utilizing HCP materials
- Positioning and assembling arrays (solar, antenna, etc.)
- Precision trace laying
- Binding alumina to aluminium wire
- Binding alumina to aluminium structural components

4. Physical Environment

RADFAB will be operating in a low-earth orbit and stay in LEO for the duration of its operation. The following nominal operating conditions are expected:

Condition	Minimum	Maximum

Temperature	-65 ℃	125 ℃
UV radiation	2220 ESH/year	5800 ESH/year
Ionizing radiation	8 Rads	16 Rads
Vacuum	10-10 Torr	760 Torr
Atomic oxygen	10^{11} atoms/m^3	10^{12} atoms/m^3
Gravity	10^{-6} g	10^{-3} g
Charged plasma environment	3x10^4 cm^{-3}, 0.1 eV particles	9x10^5 cm^{-3}, 0.2 eV particles
Available power	222W	444W
Particle impacts	11 impacts/m^2/year	26 impacts/m^2/year

The RADFAB system will need to be at least partially capable of operating under these conditions. A reduction of manufacturing speed can be expected during lower power phases of the orbit as well as during high temperature phases to prevent transducer overheating. Any conditions deviating from the above ranges will be considered off-nominal and will not be expected for functional operation. Survivability in off-nominal conditions, namely vibration conditions during launch is expected with the aid of dampening through launch packaging.

5. Support Environment

Operational planning for the mission will be performed by the student design team with the input of The Aerospace Corporation. Command of the mission will be handled by The Aerospace Corporation. The robot will be given commands through a UHF radio transmission, received by antennas attached to the RADFAB payload. Mission control will have access to real-time greyscale video of the experimental setup as well as real-time telemetry collected by the robot including toolhead force, temperature and filament status, all actuator positions and power status. The student design team will perform analysis on the performance of the system after the mission's conclusion in addition to any internal analysis The Aerospace Corporation would do. The current proposed RADFAB demonstrator unit will not be upgraded or maintained past the single mission usage and will be de-orbited upon mission completion.

6. Operational Scenarios, Use Cases and Design Reference Missions

6.1 Nominal Conditions

6.1.1. Startup

I. Power on the controller. (On-board program)
II. Test communications. (On-board program)

III. Begin diagnostic test. (Ground control)
IV. Test internal connections, voltages, temperatures, and other sensors (On-board program)
V. Send diagnostics (On-board program)
VI. Test the ultrasonic modules and test all axes' motion for functioning status and temperature (Ground control)
VII. Turn off motors and function generator (Ground control)
VIII. Enter standby mode and collect environmental data for at least one full orbit if it has not already been gathered (On-board program)

6.1.2. Tests

1. Aluminium Girder Alignment

    I. Begin aluminium girder alignment sequence (Ground control)
    II. Adjust parameters based on starting location (On-board program).
    III. Wait for appropriate temperature range (On-board program).
    IV. Home axes and set work offset (On-board program).
    V. Begin an aluminium girder alignment routine with specified settings (On-board program).
    VI. Check for pin-insert limit switch depression to ensure proper aluminium girder alignment (On-board program).
    VII. Hold girder alignment position while RADFAB tool starts cold welding process (On-board program)

2. RAD welding aluminium girder

    I. Begin welding sequence. (Ground control)
    II. Adjust parameters and starting location (On-board program).
    III. Wait for an appropriate internal temperature range. (On-board program).
    IV. Home axes and set work offset. (On-board program).
    V. Begin an aluminium girder cold welding routine with specified settings. (On-board program).
    VI. Check for conductivity/breakage continuously. Upon fault detection, change operation to bonding failure operation. (On-board program).
    VII. Move the tool to retract height when deposition completes. (On-board program).
    VIII. Turn the ultrasound off and move rapidly in X to break the wire. (On-board program).
    IX. Feed wire (On-board program)
    X. Bend wire underneath tool compression surface (On-board program)
    XI. Home axes and turn motors off. (On-board program).
    XII. Send data (On-board program).
    XIII. Enter standby mode and wait for the ground control response. (On-board program).

3. Alumina coated wire connection laying

    I. Begin alumina wire coating and laying sequence (Ground control)
    II. Adjust parameters and starting location (On-board program).
    III. Wait for an appropriate internal temperature range. (On-board program).
    IV. Home axes and set work offset. (On-board program).

V. Check for conductivity/breakage continuously. Upon fault detection, change operation to bonding failure operation. (On-board program).
VI. Move the tool to retract height when deposition completes. (On-board program).
VII. Enter standby mode and wait for the ground control response. (On-board program).

4. Solar cell positioning

   I. Begin solar cell alignment sequence (Ground control)
   II. Adjust parameters based on starting location (On-board program)
   III. Wait for appropriate temperature range (On-board program)
   IV. Begin a solar cell alignment routine with specified settings (On-board program)
   V. Check for solar cell alignment using on-board sensors (On-board program)
   VI. Maintain solar cell alignment position while RADFAB tool starts solar cell trace laying (On-board program).

5. Solar cell trace laying

   I. Begin solar cell trace laying sequence (Ground control)
   II. Adjust parameters and starting location (On-board program).
   III. Wait for an appropriate internal temperature range. (On-board program).
   IV. Home axes and set work offset. (On-board program).
   V. Begin solar cell cold welding routine with specified settings. (On-board program).
   VI. Check for conductivity/breakage continuously. Upon fault detection, change operation to bonding failure operation. (On-board program).
   VII. Move the tool to retract height when deposition completes. (On-board program).
   VIII. Enter standby mode and wait for the ground control response. (On-board program).

6. UV light test

   I. Begin UV light testing sequence (Ground control)
   II. Turn on onboard UV light (On-board program)
   III. Check for total voltage generated by both solar cells (On-board program)
   IV. Check voltage generated by each solar cell individually (On-board program)
   V. Enter standby mode and wait for the ground control response. (On-board program).

7. Aluminium coupon tensile test

   I. Begin aluminium coupon tensile test sequence (Ground control)
   II. Ensure tensile test coupon is securely fastened (On-board program)
   III. Ensure SCARA arm is in a safe position (On-board program)
   IV. Retract tensile test holder to induce material stress into welded coupon (On-board program)
   V. Record load readings in load-cell (On-board program)
   VI. Continue tensile test until material failure (On-board program)

VII. Upon material failure, halt tensile test holder movement (On-board program)
VIII. Notify ground control (On-board program)
IX. Upload relevant data and metadata to ground control (On-board program)

6.1.3. Welding Failure

I. Pause welding (On-board program)
II. Notify Ground Control (On-board program)
III. Send data to Ground Control (On-board program)
IV. Problem remedies (Ground control)
    a. Re-upload GCODE with increased compression parameter
V. If succeeds, return to operation (Ground control)
VI. Feed wire (On-board program)
VII. Cut wire by moving without feeding and with the function generator off (On-board program)
VIII. Feed wire (On-board program)
IX. Bend wire (On-board program)
X. Resume process (Ground control)

6.1.4. Send Data Operation

(assuming all data is not transmitted in real-time)

1. Data that is important to send in real-time or upon automatically detected faults (On-board program):
    I. Enclosure temperature
    II. Ground relative position
    III. Sun relative position
    IV. GCODE position
    V. Configuration version
    VI. Battery temperature
    VII. Battery voltage
2. Collect the following data during welding, wire deposition and fatigue test (On-board program):
    I. Tool position/operation
    II. Tool head force
    III. Tool/bed conductivity
    IV. Tool head temperature
    V. Motor drive currents
    VI. MCU temperature

1. Top-down image of each layer
2. Periodic infrared view of build volume (every 30 seconds)
3. Tensile stress to induce coupon joint failure

6.1.5. Transmit batch (compressed) data to ground control (Ground control)

6.1.6. Retain data on board in case of transmission error (On-board program)

6.2 Off-Nominal Conditions

6.2.1. Welding Failure

- I. Pause welding (On-board program)
- II. Notify Ground Control (On-board program)
- III. Send data to Ground Control (On-board program)
- IV. Problem remedies (Ground control)
  - a. Re-upload GCODE with increased compression parameter
- V. If succeeds, return to operation (Ground control)
- VI. Feed wire (On-board program)
- VII. Cut wire by moving without feeding and with the function generator off (On-board program)
- VIII. Feed wire (On-board program)
- IX. Bend wire (On-board program)
- X. If successful, return to standard operation, otherwise attempt next remedy (Ground Control)

6.2.2. Solar Cell Positioning Error

- I. Pause machine movement (On-board program)
- II. Notify Ground Control (On-board program)
- III. Send data to Ground Control (On-board program)
- IV. Problem remedies (Ground Control)
  - a. Upload tool-zeroing GCODE
  - b. Ensure proper gripper connection
  - c. Ensure proper solar-cell alignment
  - d. Manually align solar cell
- V. If successful, return to standard operation, otherwise attempt next remedy (Ground Control)

6.2.3. Tensile Test Coupon Positioning Error

- I. Pause machine movement (On-board program)
- II. Notify Ground Control (On-board program)
- III. Send data to Ground Control (On-board program)
- IV. Problem remedies (Ground Control)
  - a. Upload tool-zeroing GCODE
  - b. Ensure proper gripper connection
  - c. Ensure proper tensile coupon alignment
  - d. Manually align tensile coupon
- V. If successful, return to standard operation, otherwise attempt next remedy (Ground Control)

6.2.4. Communications Failure

- Signal Interference
  - I. Pause machine movement (On-board program)

II. Attempt to notify ground control (On-board program)
III. Determine cause (Ground control)
IV. Problem remedies (Ground control)
   a. Modify ground control broadcast frequency shift from lower VHF to SHF
   b. Wait for satellite to reposition
   c. Wait for conditions to improve
V. If successful, return to standard operation, otherwise attempt next remedy (Ground Control)

- Partial Communications Failure
   I. Pause machine movement (On-board program)
   II. Attempt to notify ground control (On-board program)
   III. Problem remedies (Ground control)
      a. Re-upload failing program
      b. Re-flash firmware
   IV. If successful, return to standard operation, otherwise attempt next remedy (Ground Control)

6.2.5. Tool Breakage

I. Pause machine movement (On-board program)
II. Notify ground control (On-board program)
III. Transmit imagery of tool to ground control (On-board program)
IV. Evaluate tool breakage severity (Ground control)
V. Problem remedies
   a. Modify RADFAB operation parameters to compensate for tool breakage
   b. Terminate mission and begin deorbiting procedure
VI. If successful, continue operation, otherwise attempt next remedy (Ground control)

6.2.6. Battery Malfunction

I. Pause machine movement (On-board program)
II. Notify ground control (On-board program)
III. Transmit battery voltage, amperage, temperature and charge level to ground control (On-board program)
IV. Compare readings with expected battery performance (Ground control)
V. Verify undamaged, unobstructed solar panels (Ground control)
VI. Run diagnostics on Battery Management System (On-board program)
VII. Problem remedies
   a. Attempt controlled charge and discharge cycles to recalibrate (On-board program)
   b. Decrease operation speed (Ground control)
   c. Limit RADFAB operation to periods of direct sunlight (Ground control)
VIII. If successful, return to standard operation, otherwise attempt next remedy (Ground control)

6.2.7. Software Failure

I. Pause machine movement (On-board program)

II. Notify ground control (On-board program)
III. Ensure proper uplink and downlink functionality (Ground control)
IV. Upload telemetry and software logs (On-board program)
V. Analyze telemetry and data logs (Ground control)
VI. Problem remedies
    a. Attempt soft reboot (Ground control)
    b. Re-flash firmware (Ground control)
    c. Reupload G-code (Ground control)
    d. Roll back software version (Ground control)
    e. Upload patched program (Ground control)
VII. If successful, return to standard operation, otherwise attempt next remedy (Ground control

6.2.8. Thermal Failure

I. Pause machine movement (On-board program)
II. Notify ground control (On-board program)
III. Upload temperature readings (On-board program)
IV. Compare temperature readings to historical data (Ground control)
V. Run electrical system diagnostics (On-board program)
VI. Assess radiator position (Ground control)
VII. Assess radiator integrity (Ground control)
VIII. Assess environmental factors (Ground control)
IX. Determine excess heat origin (Ground control)
X. Remedies
    a. Adjust satellite orientation (Ground control)
    b. Adjust power consumption (Ground control)
    c. Restart thermal management system (Ground control)
    d. Attempt total soft reboot (Ground control)
    e. Enter system hibernation until temperature returns to operational level (Ground control)
XI. If successful, return to standard operation, otherwise attempt next remedy (Ground control)

6.2.9. Wire breakage

I. Pause machine movement (On-board program)
II. Notify ground control (On-board program)
III. Upload extrusion motor voltage (On-board program)
IV. Remedies
    a. Enable ultrasound, retract and then re-feed wire (Ground control)
    b. Enable ultrasound, cut, and re-feed wire (Ground control)
V. If successful, return to standard operation, otherwise attempt next remedy (Ground control)

7. Impact Considerations

7.1 Environmental Impacts

The environmental impact of this system would be limited to the launching of the RADFAB demonstrator unit and the de-orbiting procedure. No additional debris or emissions are projected to be generated during the system lifecycle.

7.2 Organizational Impacts

The RADFAB demonstration mission would require hiring specialists in RAD technology to develop space-ready toolheads. Outsourcing would also need to be performed to design a robotic arm which can meet the design specifications of this mission. Blue Canyon Space will be involved with supplying the satellite bus.

7.3 Scientific/Technical Impacts

Successful completion of this mission will provide information on the performance of RAD and SSCC technology in LEO environments, as well as a successful demonstration of the technology in an ISAM perspective. Demonstration of robotic assembly of structures will also be obtained from successful mission completion. These demonstrations will allow for the development of further production RADFAB units which present the capability to design spacecraft with reduced geometric and mechanical constraints.

8. **Risks and Potential Issues**

RAD and SSCC technologies are proprietary to the Future Manufacturing Research Laboratory and Reverb Industrial. This will make finding staff with specialization in space-ready RAD toolheads difficult, and technology transfer of proprietary information between these organizations and Aerospace Corporation may be required.

9. **Appendix A: Acronyms**

AWG – American Wire Gauge

BCT – Blue Canyon Technologies

COSMIC – Consortium for Space Mobility and ISAM Capabilities

C3 – COSMIC Capstone Challenge

ESH – Equivalent Sun Hours

HCP – Hexagonal Close-Packed

ISAM – In-space Servicing, Assembly and Manufacturing

IR – Infrared Radiation

LED – Light Emitting Diode

LEO- Low Earth Orbit

PCB – Printed Circuit Board

RAD – Resonance Assisted Deformation

RADFAB – Resonance Assisted Deformation Fabrication

RMS – RAD Motion System

SSCC – Solid State Ceramic Coating

TRL – Technology Readiness Level

10. Acknowledgements

Team RADFAB thanks the mentorship of Ryan Benson and the support of the Future Manufacturing Research Lab during this project.