METAL PROCESSING.
IN SPACE. FOR SPACE.

CISLUNAR INDUSTRIES

Modular Space Foundry Experimental Design For Metal Casting on the International Space Station

2024 Space Resources Roundtable

June 7, 2024

Joe Pawelski
CTO

Needs of Any New Industrial Economy

Orbital, Lunar, and Planetary In-Situ Resource Utilization

- Metal materials processing
- Propellant production
- End-of-life disposal
- Power infrastructure

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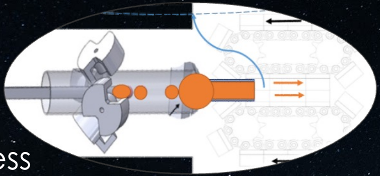
	Extraction	Hosting		Logistics	Manufacturing
In Orbit	Space Debris Removal & Transport	Commercial Space Stations, Spacecraft	Space Foundry	Storage Depot & Transport	Manufacturing & Construction
On Moon	Lunar Metal Extraction	Lunar Bases, Rovers, Landers	Metal Processing		

MSF (Modular Space Foundry)

Key Characteristics

- In-space metal foundry
- Electromagnetic induction processing of most conductive materials
  - Heats
  - Manipulates
  - Can be contactless



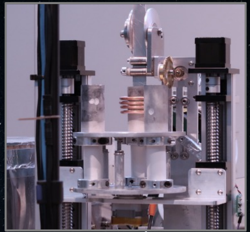
Inputs: RSO (Resident Space Object)

- Significant metal mass already in space
- Upper stages, ISS payloads, Lunar landers
- Aluminum alloys are most common

Outputs: MSF (Primary)

- 25mm bar for billets (used for wire extrusion)
- 50mm rod for metal propellant

2021



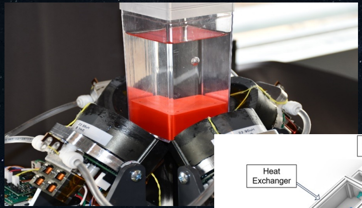
2022

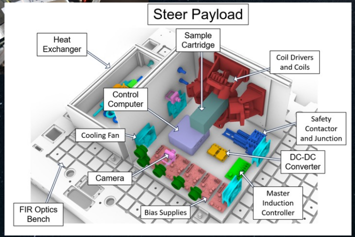
Metal foundry and continuous casting hardware for in-space operation

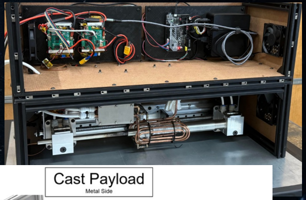
2022

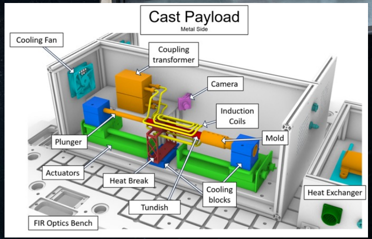
Nov 2022 – Zero-G flight continuous casting & EM steering

2023 to Present





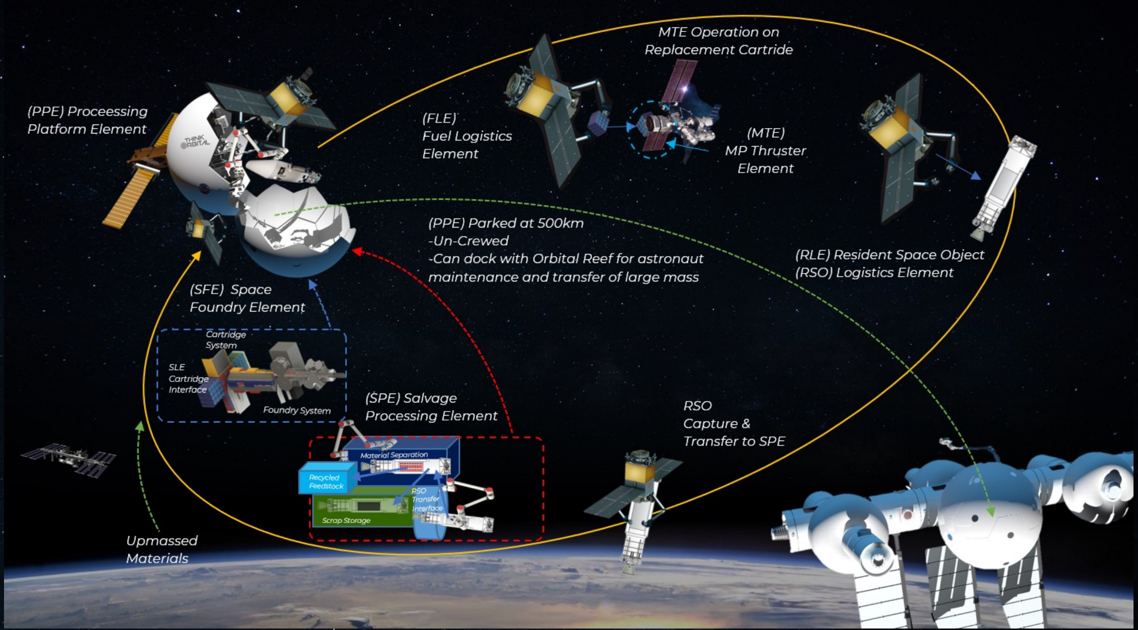




Metal Propellant Ecosystem

Overall Objectives

- Develop an orbital ecosystem to reuse and recycle spent upper stages, satellites, Resident Space Objects (RSO).
- Transform dangerous "debris" into DeltaV and feedstock for on-orbit manufacturing

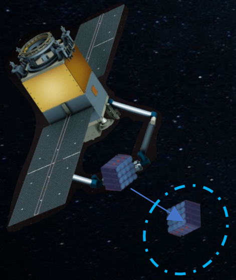


Ecosystem Technology

- End of life solution alternative to de-orbit
- Reconfigure orbital assets and reuse for new missions
- Produce metal propellant from mass that is not reused or reconfigured
- Station keeping with salvaged RSO
- "Refuel" and life extension with shelf stable propellant cartridges

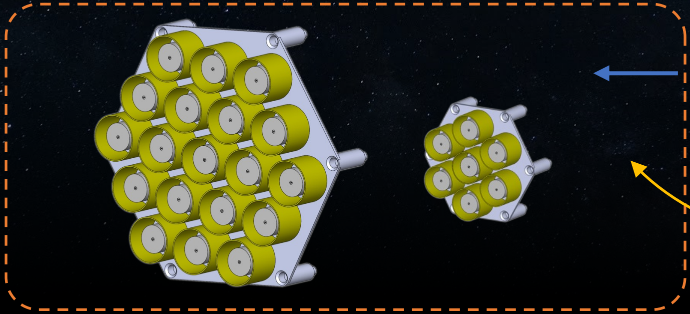
Metal Propellant Performance

Propellant	Cartridge Rod Capacity	Thruster Power (W)	Total Propellant Mass (Kg)	Impulse, kN*s	Thrust (mN)	Cartridge Size, flat to flat (CM)	Size (Area) cm	Cartridge plate Thickness	Cartridge Leg and connector Mass	Catridge Mass	Area Ratio	Mass Ratio (Big is good)	Loaded Cartridge mass (kg)
Aluminum	7	1400	1.9	24	4	34.4	1025	0.3	0.6	1.8	60.7	1.1	3.7
Aluminum	19	3800	5.2	64	11	41.26	1474	0.3	0.6	2.3	60.7	2.2	7.6
Molybdenum	7	1400	7.0	86	8	34.4	1025	0.3	0.6	1.8	60.7	3.9	8.8
Molybdenum	19	3800	19.0	233	23	41.26	1474	0.3	0.6	2.3	60.7	8.2	21.4



RSO Input = 500 kg, 2kg/hr

****Cartridge Materials = 175kg***

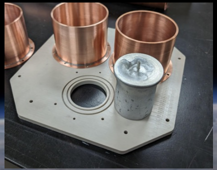


Output: 12 per 24hr-day

~130 carts, 2 weeks
~3380/yr

1 Cart = 64Kn*s
10T sat = 6.4 m/s DV
Est Station Keeping DV for Hubble and similar per year, 4.7 m/s DV

****96 Empty Cart + Trigger Pins = 175kg***

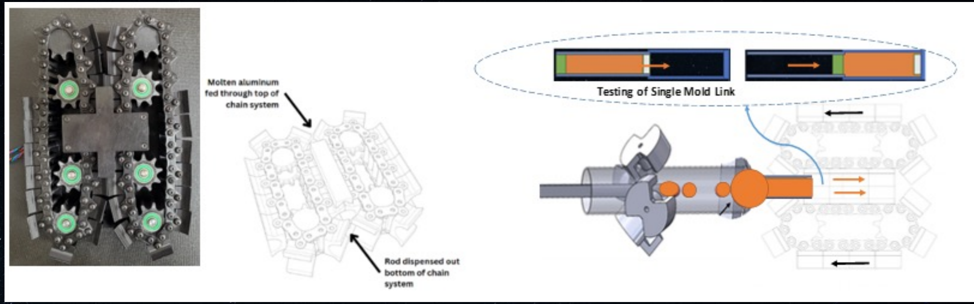


Vacuum Test Article

ISS Cast Objectives

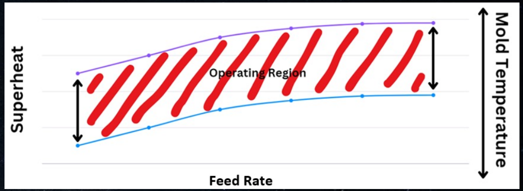
Mission Objectives

- Cast twelve 25mm samples in microgravity aboard the ISS,
    - Demonstrate cast system and verify operational parameters
    - Compare ISS Cast samples to terrestrial "chain" cast samples
    - Analyze grain structures and measure mechanical properties
    - Identify the preferred operating region for operation in sustained microgravity.



"Chain Cast" continuous casting method

MSF Casts with various casting parameters



MSF Process Parameters

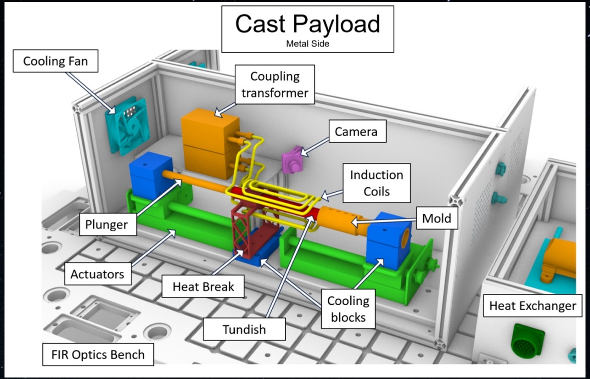
ISS Cast Payload

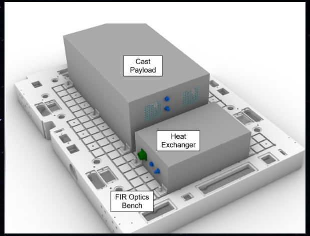
Cast Payload Operation

- Cast system includes 12 pre-loaded cartridges
  - One cartridge per experiment
  - Experiment parameters can be adjusted between experiments
  - Cartridges are returned to earth for analysis

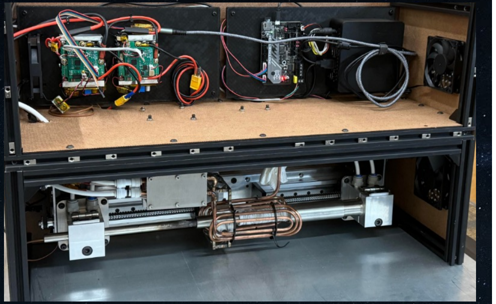
Mission Preparation

- Ongoing safety review with NASA and ZIN
- Parabolic subsystem verification ISS payload flight November 2024
- Parabolic full ISS Payload flight verification February 2025
  - Flying ISS Payload as "Dress Rehearsal"

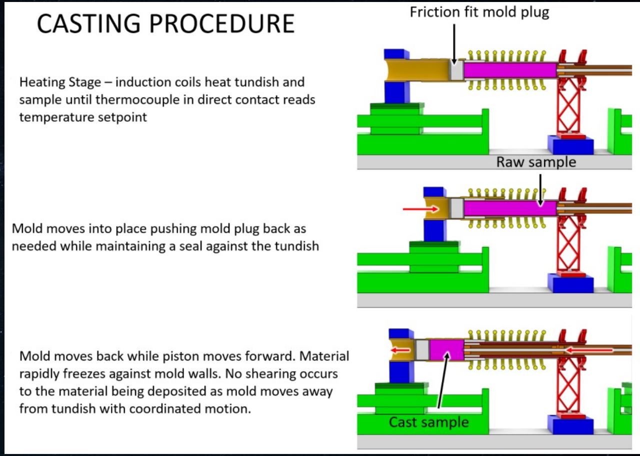




Render of ISS Cast Payload installed in FIR



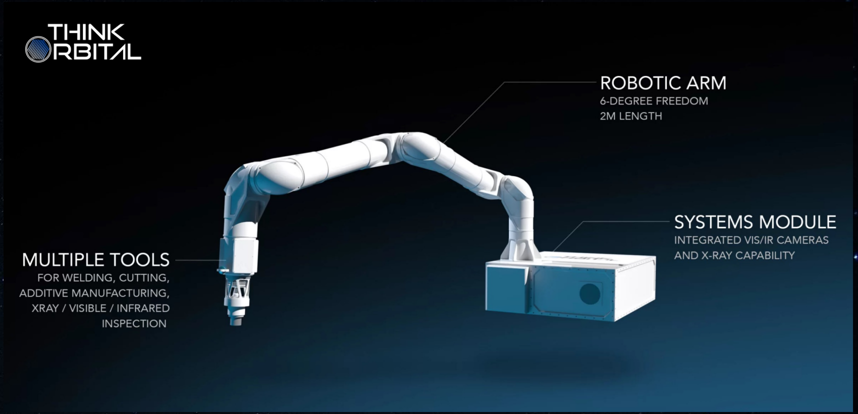
Functional Prototype of ISS MSF



Feeding the Foundry

Capturing Space Debris

- How are large tumbling objects captured?
  - Astroscale US helped inform the Con-Ops for capture of space debris
- After capture, salvaging operations commence
  - Nanoracks friction spin cutting
  - Think Orbital EBeam cutting



Metal Manipulation

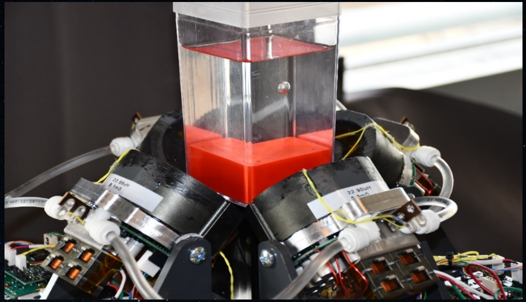
- How to manipulate chips and strips?
  - Flexibility for various sizes
  - Not getting hung up
  - Lasting for as long as possible in such a harsh environment

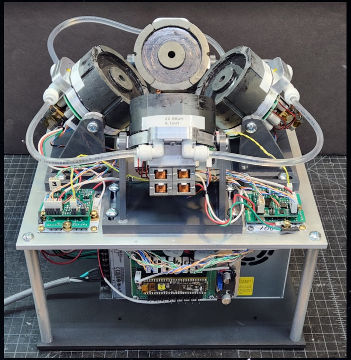
Feeding the Foundry

Continued

Moving Metal

- How best to go about manipulating molten aluminum through a microgravity environment?
    - Contactless transportation of hazardous materials

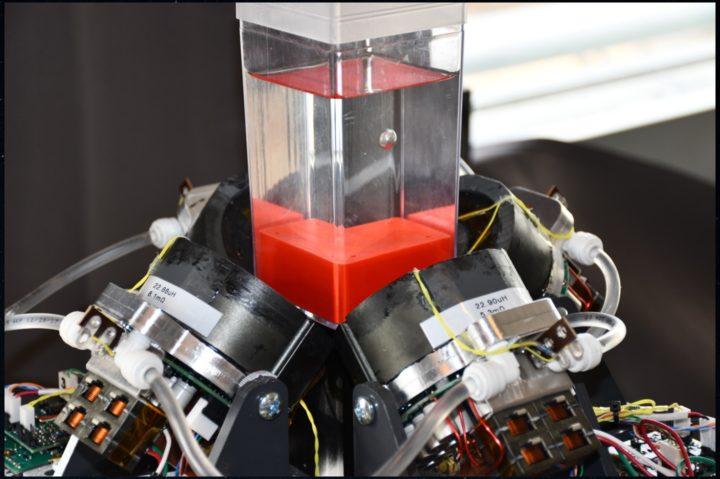




Future Capabilities

- How does the capability to manipulate molten metals enable:
    - AM
    - Unique casting technologies
    - Various Alloys, Shapes, Etc.
    - Anything different from in orbit casting processes

Steer Using Coil Array:
3D Position Control

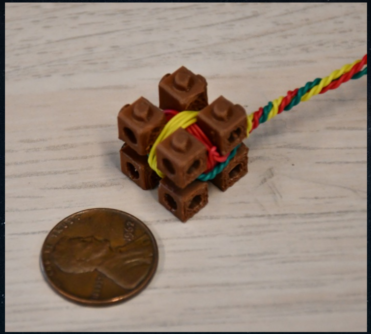


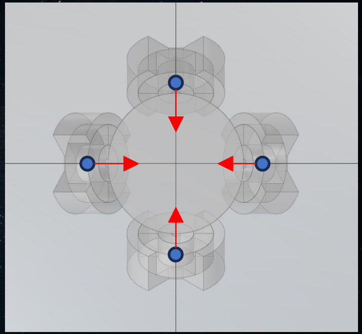
Year 1 Milestones:

- Created a simulated microgravity environment by leveraging buoyancy
- Calibrated system to account for distortion due to ferrite cores
- Developed a mathematical model to determine the required coil current values to generate an arbitrary force in the calibrated workspace
- Verified results in simulation

$$\bar{F} = 2\|g_c\|\frac{cos\gamma}{2}\left[\mathbb{B}\vec{I}\right]_f\overrightarrow{\mathbb{G}I}$$

$$g_c = \frac{2\pi i\omega\sigma a}{k^4}\left(a^2k^2 - 3 + akcot(ak)\right)$$

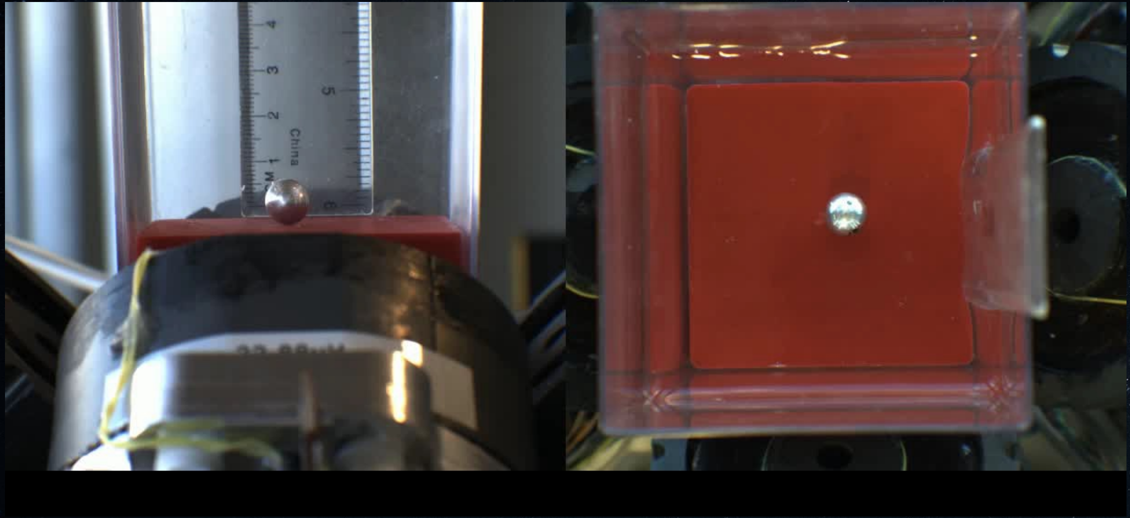


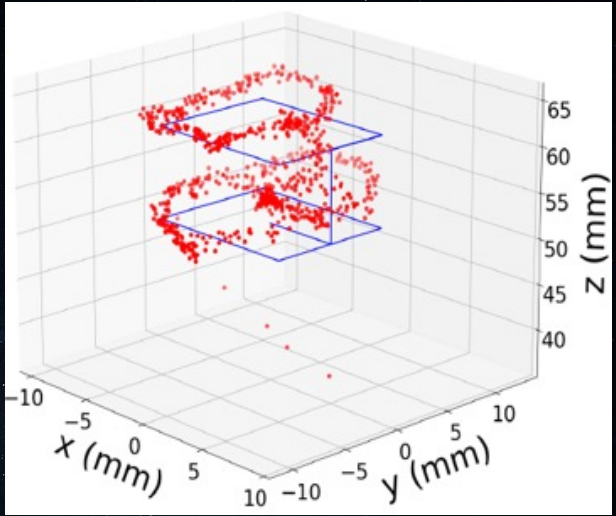


Steer Using Coil Array:
3D Position Control

Year 2 Milestones:

- Demonstrated Open-Loop control of a semi-buoyant sphere using stable solutions

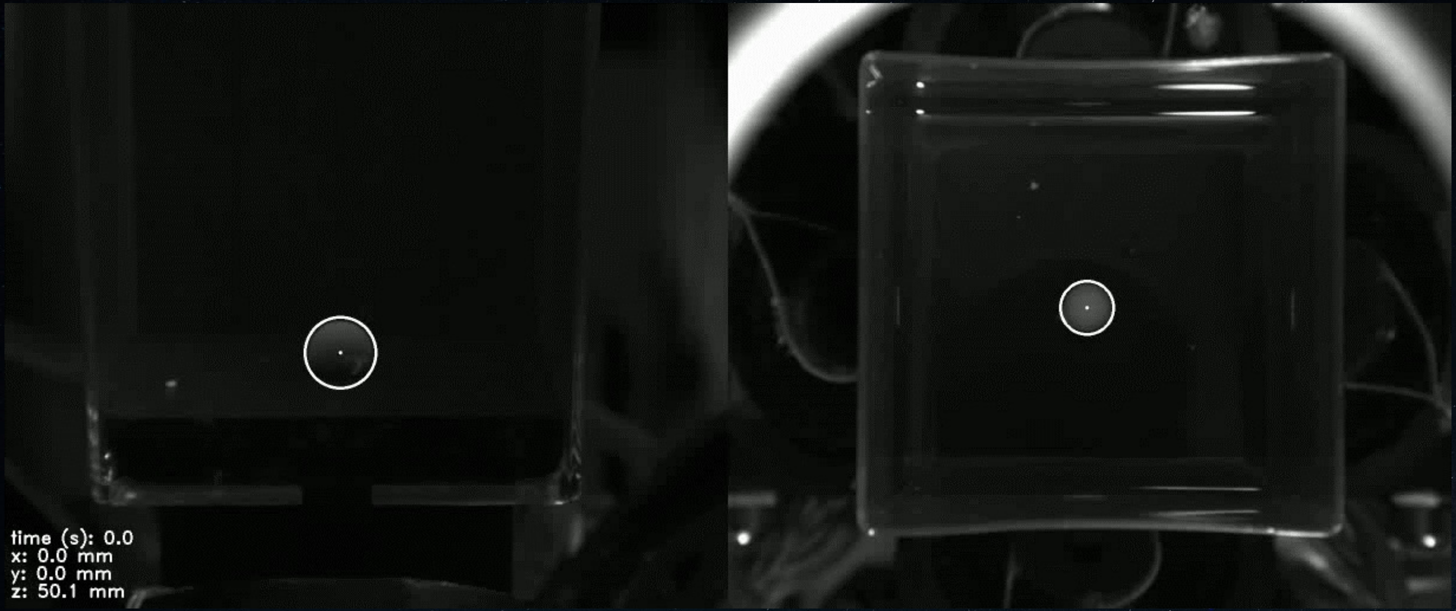


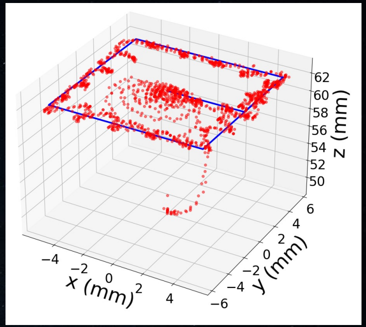


Steer Using Coil Array:
3D Position Control

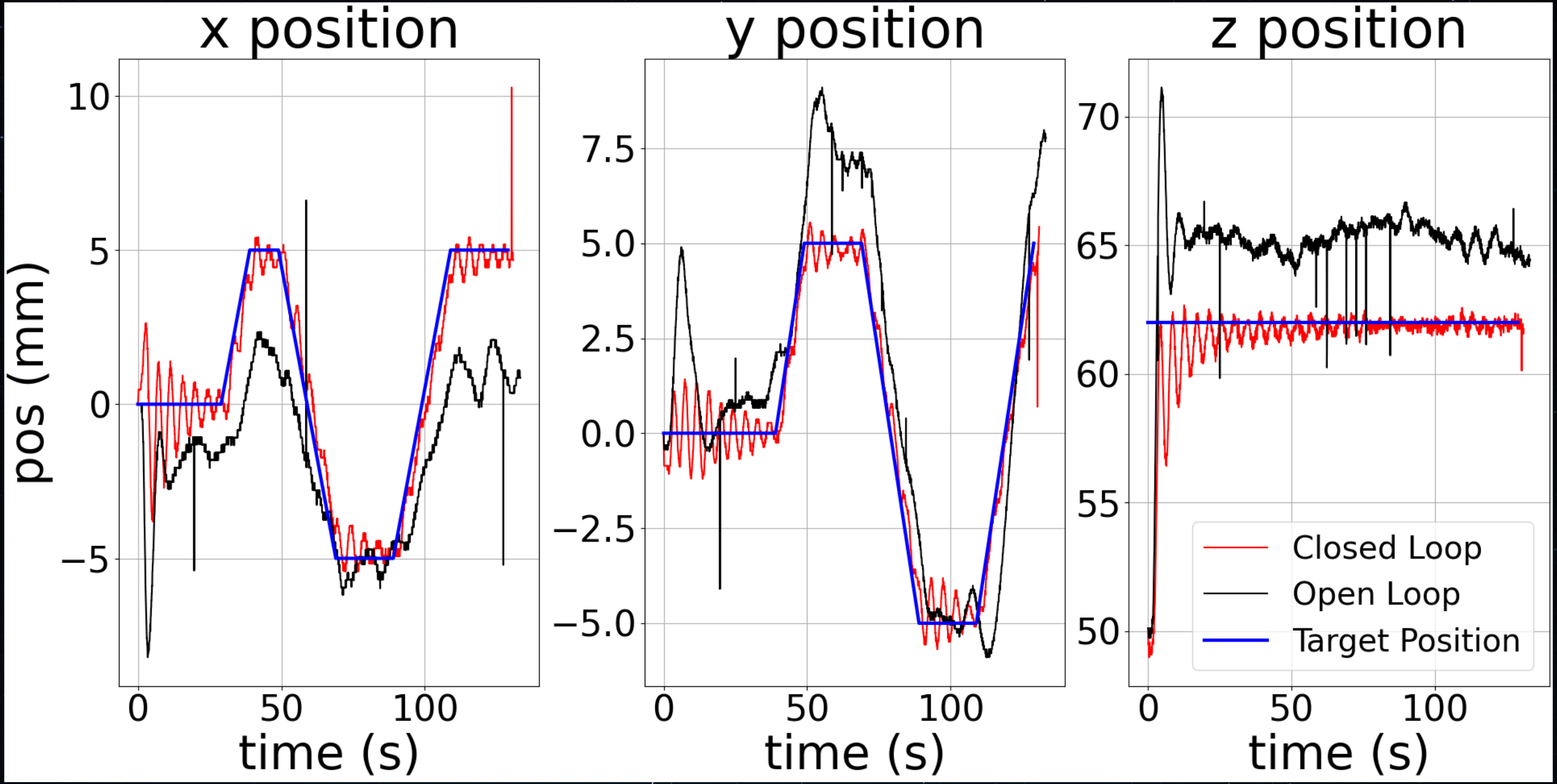
Year 2 Milestones:

- Demonstrated Closed-Loop control in 3D space using a PID controller





Steer Using Coil Array:
3D Position Control



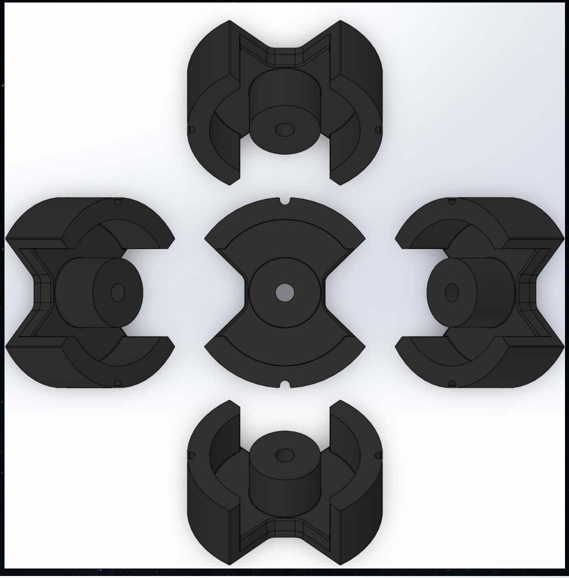
Steer Using Coil Array:
3D Position Control

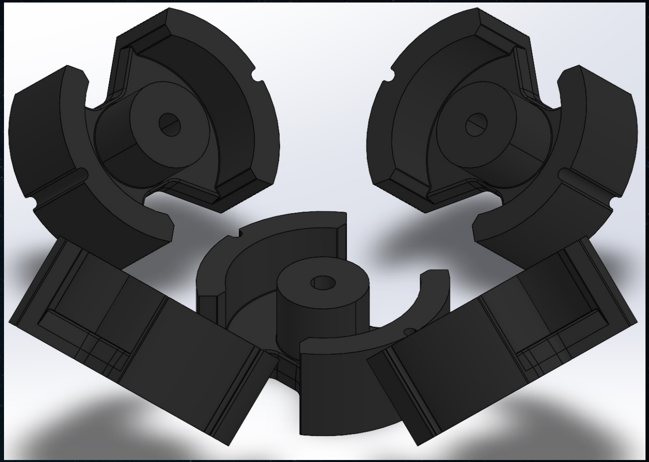
ISS Flight Objectives:

- Add 5th coil for increased control and field/gradient magnitudes
- Verify position control using various sized spheres with varying electrical conductivity
- Verify both open and closed-loop algorithms
- Generate data on the response of liquid metals to applied fields and gradients in microgravity
- Demonstrate melting using 5 coil array

Future Possibilities:

- Guiding molten metals into molds/casting processes
- 3D printing with molten metals in microgravity
- Shaping molten metals themselves
- Capturing/maneuvering satellites





Questions?

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Visit Seth at the M3 Robotics lab to see Steer in action!

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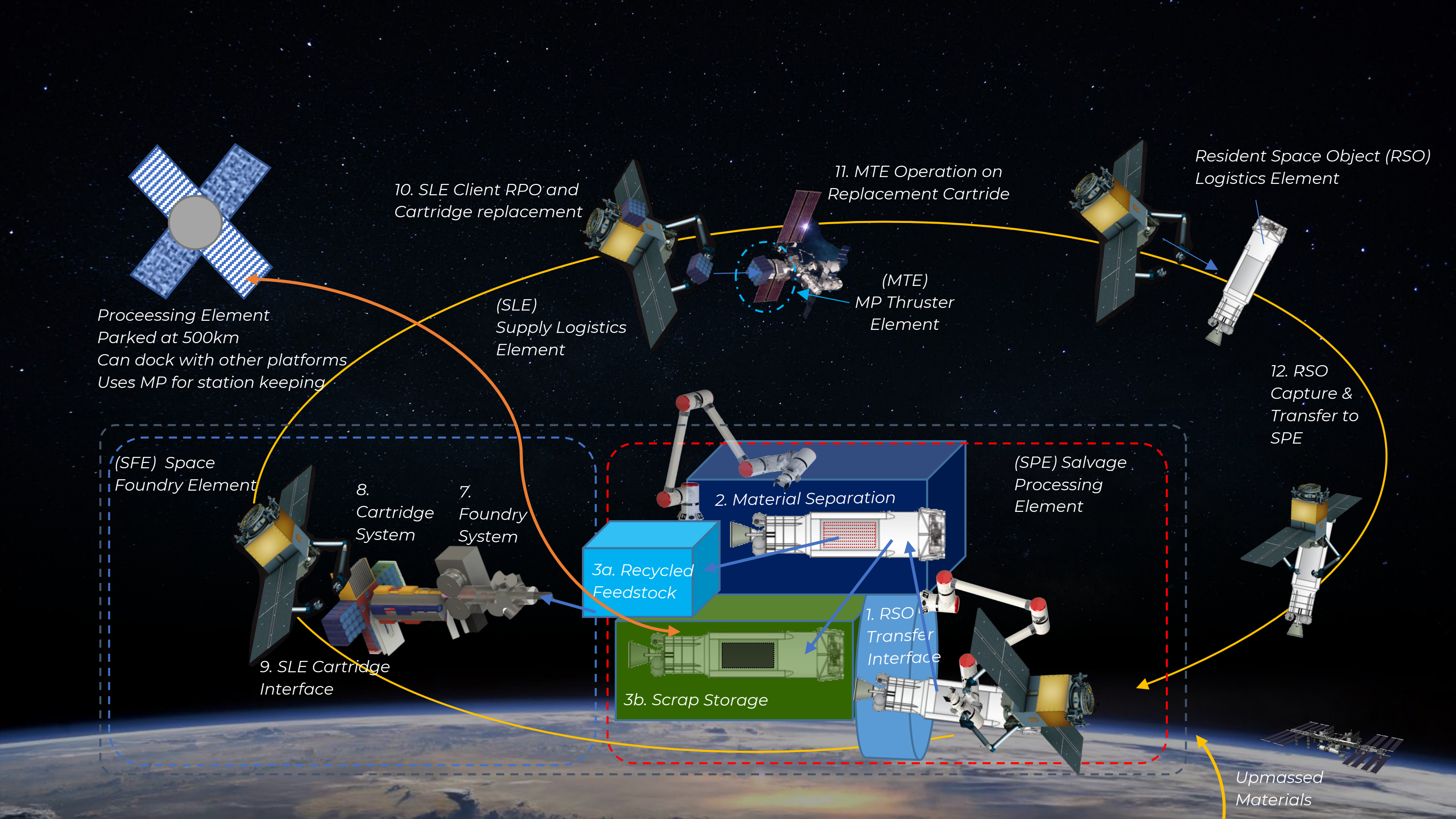
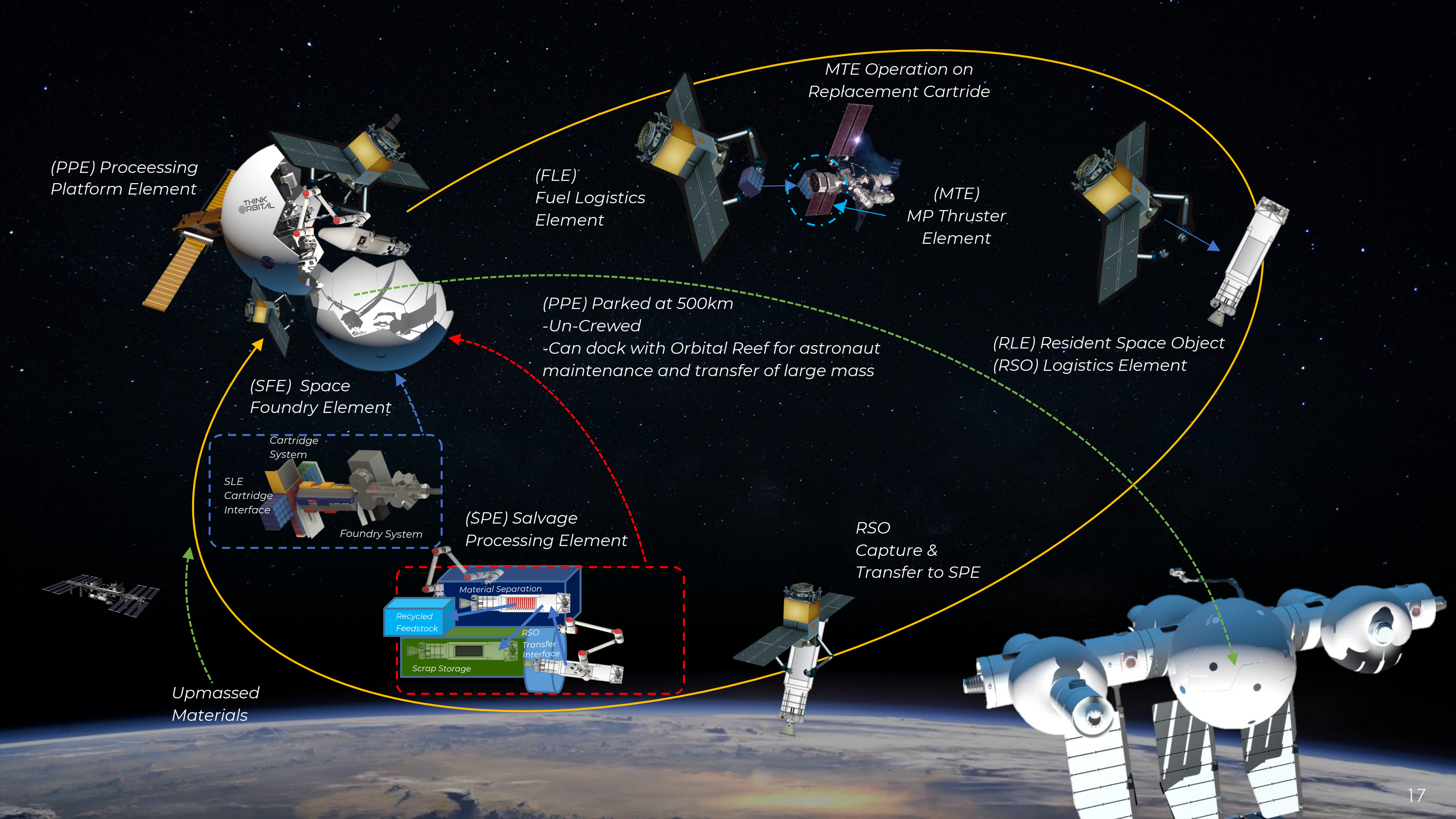


10. SLE Client RPO and Cartridge replacement
11. MTE Operation on Replacement Cartride
Resident Space Object (RSO) Logistics Element
Proceessing Element
Parked at 500km
Can dock with other platforms
Uses MP for station keeping
(SLE) Supply Logistics Element
(MTE) MP Thruster Element
12. RSO Capture & Transfer to SPE
(SFE) Space Foundry Element
8. Cartridge System
7. Foundry System
2. Material Separation
(SPE) Salvage Processing Element
3a. Recycled Feedstock
1. RSO Transfer Interface
9. SLE Cartridge Interface
3b. Scrap Storage
Upmassed Materials


MTE Operation on
Replacement Cartride
(PPE) Processing
Platform Element
THINK
ORBITAL
(FLE)
Fuel Logistics
Element
(MTE)
MP Thruster
Element
(PPE) Parked at 500km
-Un-Crewed
-Can dock with Orbital Reef for astronaut
maintenance and transfer of large mass
(RLE) Resident Space Object
(RSO) Logistics Element
(SFE) Space
Foundry Element
Cartridge
System
SLE
Cartridge
Interface
Foundry System
(SPE) Salvage
Processing Element
RSO
Capture &
Transfer to SPE
Material Separation
Recycled
Feedstock
RSO
Transfer
Interface
Scrap Storage
Upmassed
Materials