University of Michigan

Michigan In-Space Servicing Orbiter

Final Presentation

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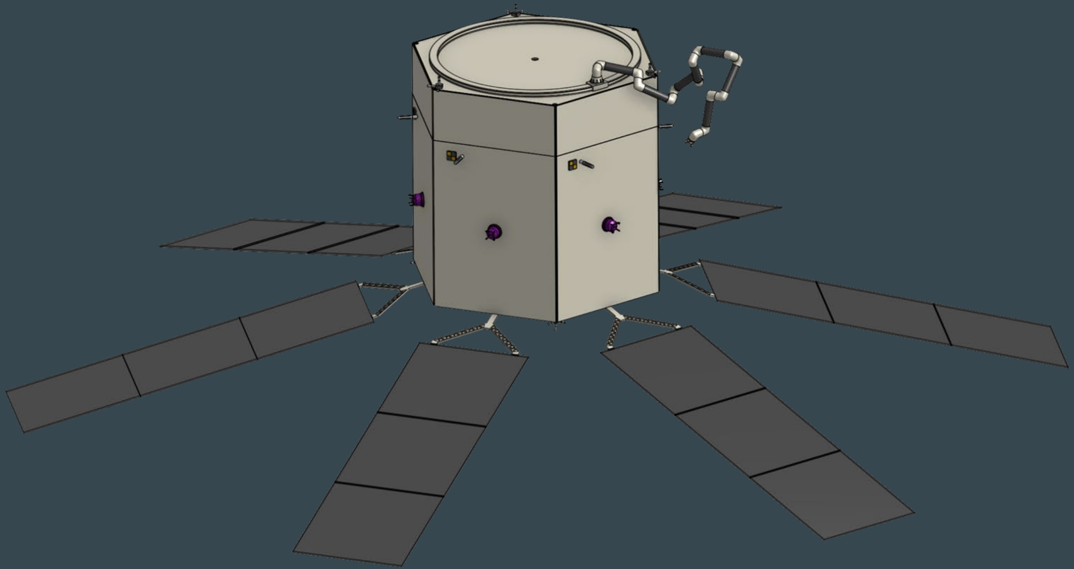
Agenda

- Executive Summary
- Program Overview
- Business Feasibility
- Operating Sequence
- System Design
- Engineering Development
- Development Plan
- Lessons Learned



Executive Summary

Problem:

- Spacecraft are single-use and mass-constrained
- Lifetimes of agile on-orbit servicers are fuel-constrained
- Critical components are not serviceable or replaceable

Proposed Solution:

- An orbiting depot for transfer of propellant and components
- Supports on-orbit servicers' mission of enabling lighter, more resilient spacecraft
- **Current Status:** completed conceptual design and analysis

Our proposal will be a foundation which supports rapid growth of ISAM.

Program Overview

Team Overview


Devin Mroz
Project Manager


Serabi Francis
Systems Engineering


Tao Sevigny
Mission Architecture


Ethan Landt
Technical Integration


Yuvraaj Pasumarthy
Technical Integration


Prof. Aaron Johnson
Faculty Advisor


Ayush Pujara
Orbital Mechanics


Armita Marpu
Robotic Systems


Jina Patel
Propellant Systems
Business Lead


Calvin Wong
Mechanical Systems


Dr. Ed Tate
Industry Advisor

Program Management [2.4]

Team Formation September	SRR November	Trade Studies December	Architecture Selection January	CoDR March	Path to F April
Roles assigned Initial mission scope defined ***Selected operations and capabilities***	Initial requirements established ***Reformed mission scope***	Docking interfaces, propulsion, comms, architecture trades ***Finalized operations and capabilities***	***System requirements defined*** Multiple architectures developed	***Trade studies completed*** Thermal + radiation analysis ***Finalized conceptual design***	Identified risks + next steps Plan for design refinement & validation

Demonstrates a complete progression from requirements definition to a validated baseline design, aligned with standard aerospace program milestones.

Advancing High-Value Missions [1.4]

Primary Mission Objectives:

1. Demonstrate on-orbit propellant storage and transfer.
2. Demonstrate on-orbit component storage and transfer via robotic arm.

This mission advances ISAM capabilities by extending satellite lifetimes through on-orbit refueling and modular component replacement. It supports sustainable, scalable space infrastructure while reducing reliance on Earth-based resupply.

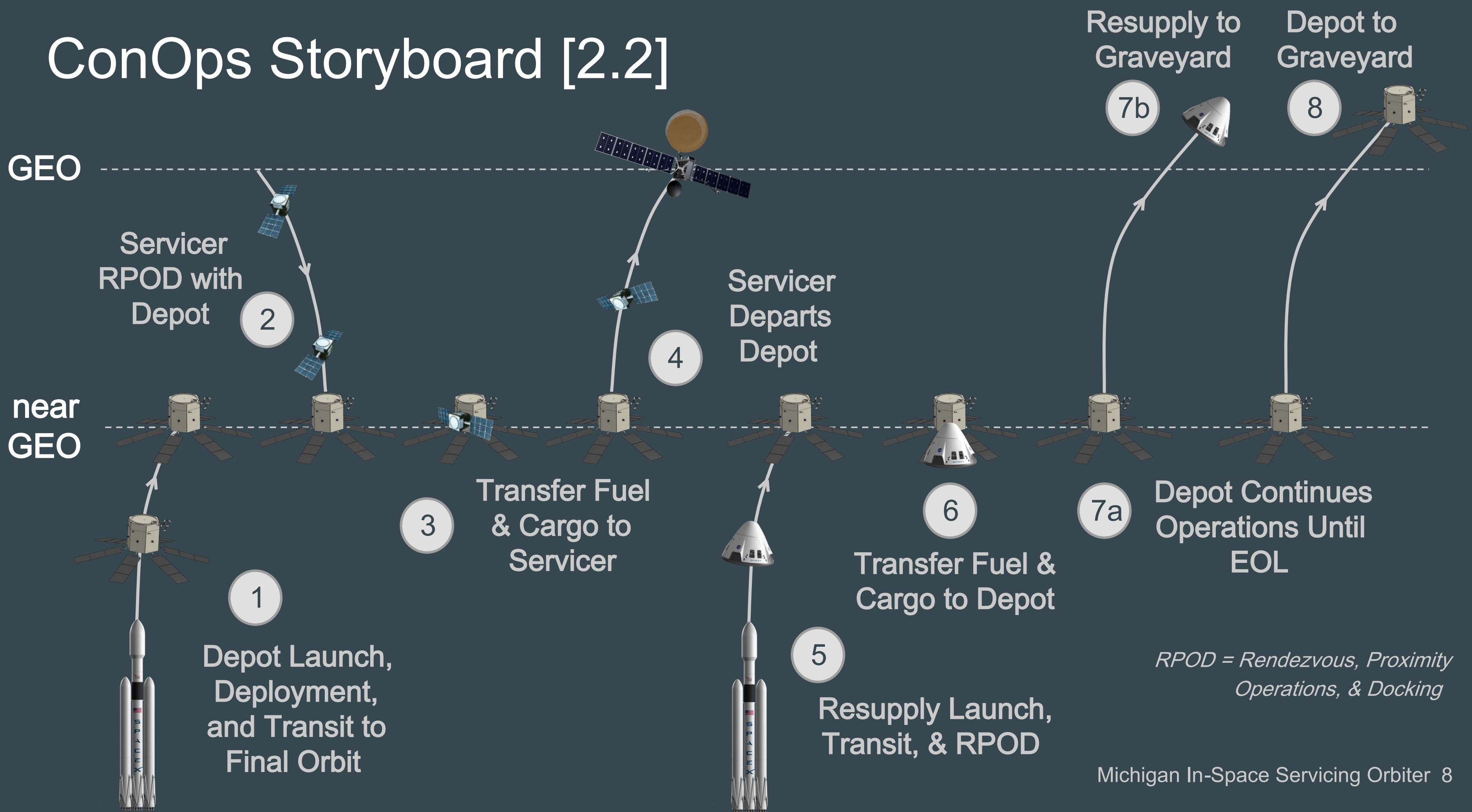
Our design introduces a dual-function platform that integrates refueling and component transfer, enabled by a robotic arm and standardized servicing interfaces compatible with multiple clients.

Our mission directly advances the following COSMIC objectives:

- Promote coordinated development and demonstration of new ISAM technologies
- Facilitate access to digital, ground, and space test opportunities and infrastructure to transform technologies into fielded capabilities
- Incubate and encourage promising technologies with applications to new ISAM markets
- Facilitate transfer of ISAM technologies to commercial market

COSMIC
CONSORTIUM FOR SPACE MOBILITY
AND ISAM CAPABILITIES

ConOps Storyboard [2.2]



1 Depot Launch, Deployment, and Transit to Final Orbit

2 Servicer RPOD with Depot

3 Transfer Fuel & Cargo to Servicer

4 Servicer Departs Depot

5 Resupply Launch, Transit, & RPOD

6 Transfer Fuel & Cargo to Depot

7a Depot Continues Operations Until EOL

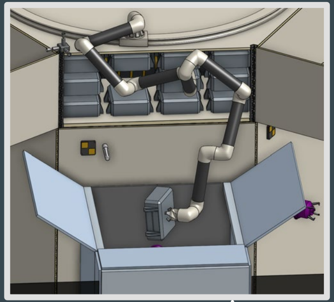
7b Resupply to Graveyard

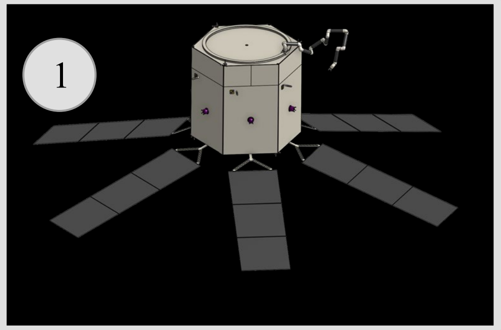
8 Depot to Graveyard

RPOD = Rendezvous, Proximity Operations, & Docking

Client Servicing Storyboard [2.2]

Stages -13 → Docking and Refueling
Stages -16 → Docking and Component Handoff

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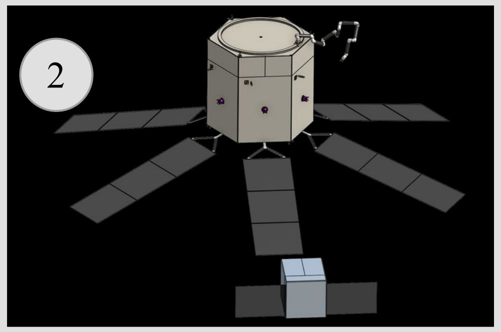
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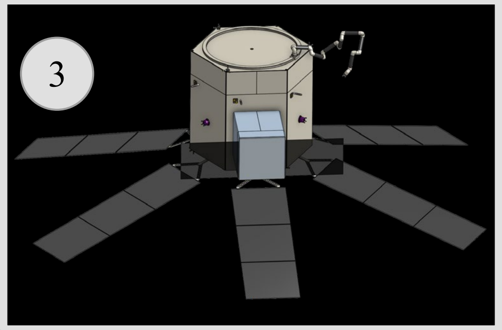
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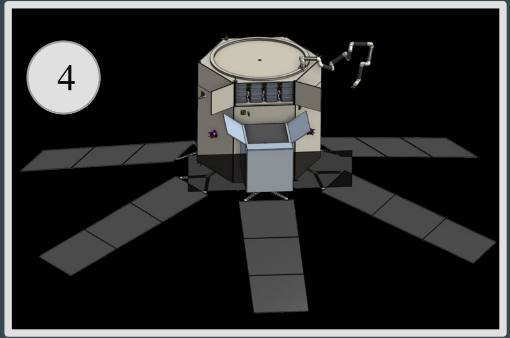
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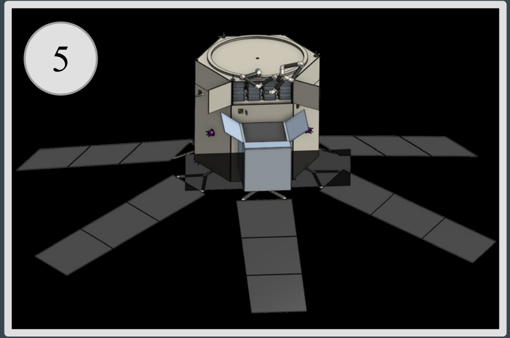
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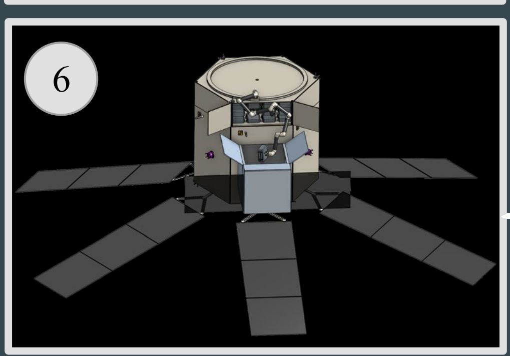
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Business Feasibility (1 of 2)

Development & Launch Cost: ~$1.1B

- Primary drivers:
    - Manufacturing
    - Launch
    - Contingencies for first-of-its-kind system

Lifetime Operations Cost: ~$550M

- Primary drivers:
    - Insurance
    - Mission Ops

Total Cost: ~$1.65B USD

Pricing Model	
Propellant	
Competitor price per kg	$200,000
MISO price per kg	**$100,000 to $170,000**
Solar Arrays	
Competitor price per module	~$17-18M
MISO price per module	**$6M to $10M**
Batteries	
MISO price per module	**$3M to $5M**
Antennas	
MISO price per module	**$10M to $20M**
Storage Service	
Price per m^3 per month stored	**$10,000 to $50,000**
Annual Membership	
Tier 1 (Executive)	**$50M**
Tier 2 (Standard)	**$25M**

Initial Launch Cargo:

- 7,000 kg hydrazine
- 3 sellable components (1 of each)

Business Feasibility (2 of 2)

Development + Operations:

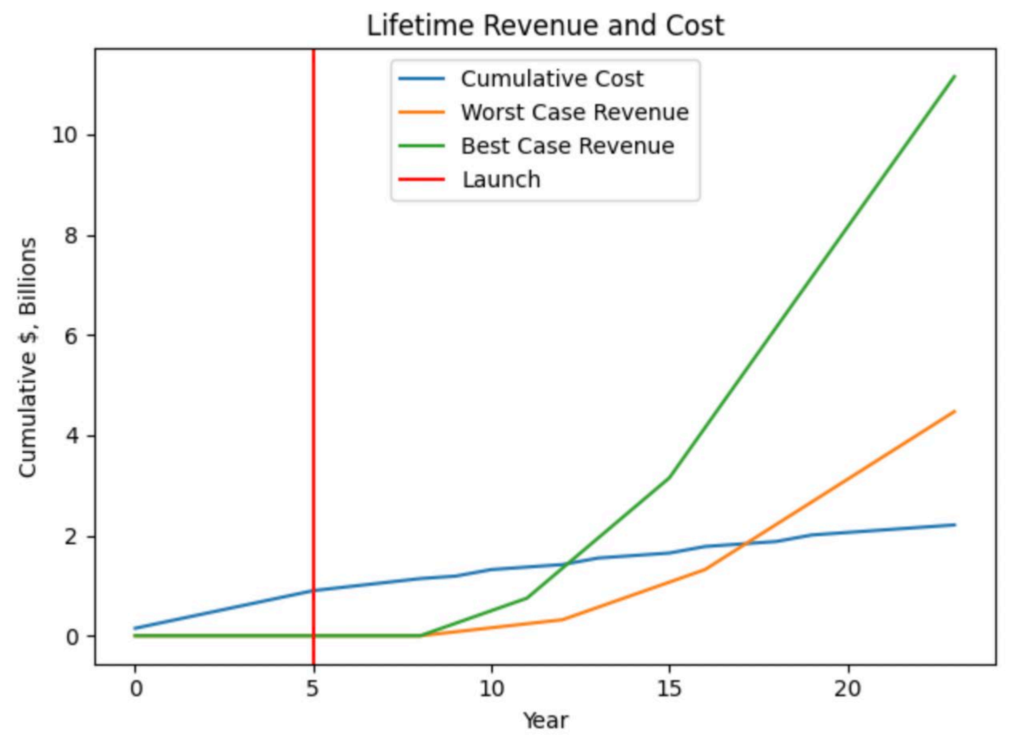
- ~$1.65B total development + operations cost
- ~$45M-$110M per resupply mission using rideshares
- High upfront investment consistent with SMAD lifecycle

Break-Even Point:

- Occurs after Year 12
- ~4 years after orbit insertion

Long-Term Performance:

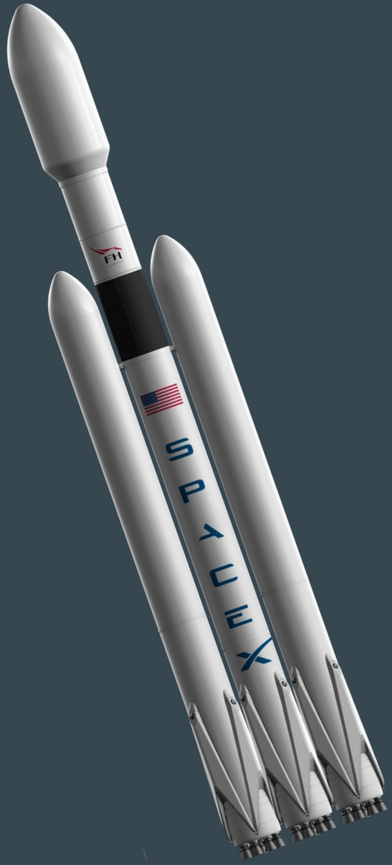
- Total revenue: **$5.4$8.7B+**
- Strong positive cash flow after break-even



Operating Sequence

Launch and Orbit Insertion

- The depot will be launched by Falcon Heavy into an elliptical transfer orbit
  - Perigee: 185 km
  - Apogee: 34,786 km
- It will use its EP thrusters to circularize at 34,786 km over roughly 3 years



Client Maneuvers

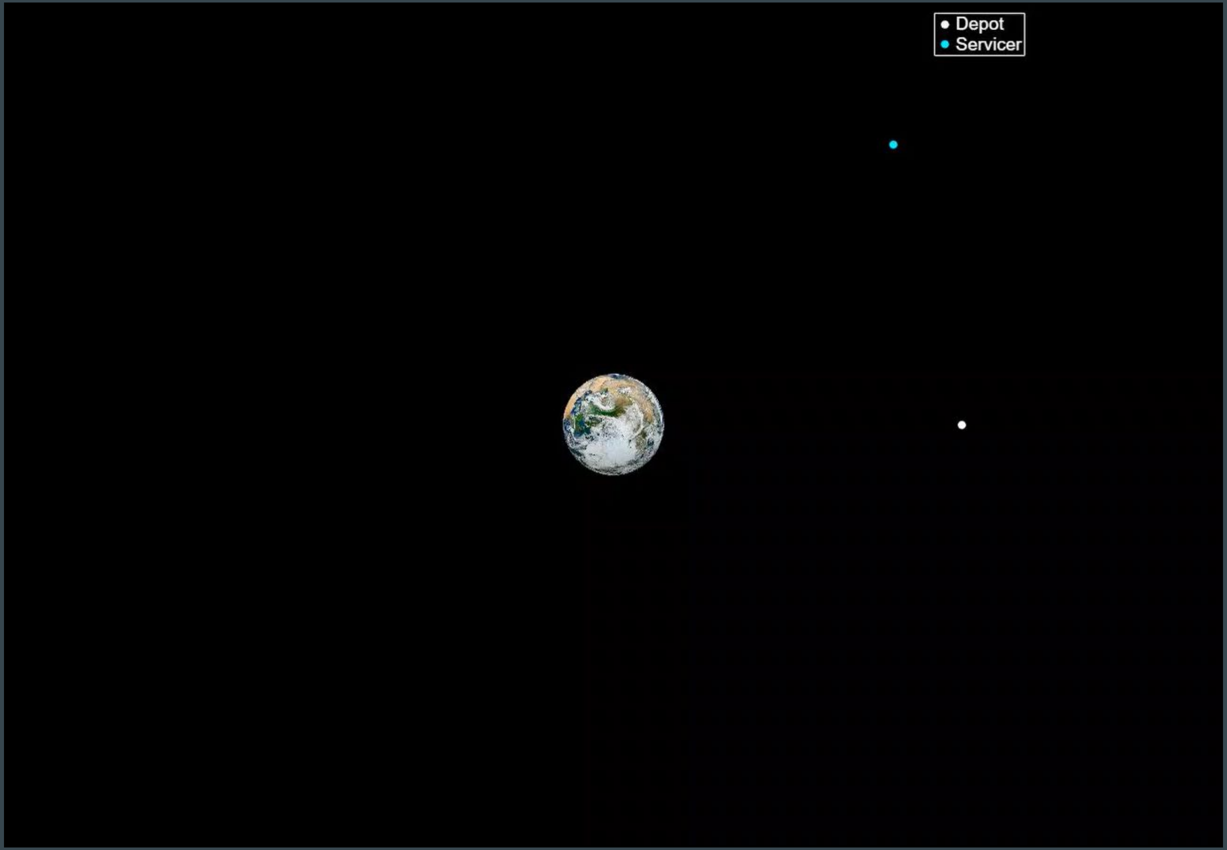
Sequence of Events:

- Client waits for proper alignment
- Client performs burn to enter elliptical transfer orbit
- Client performs burn to circularize orbit upon reaching depot orbit
- Client enters phasing orbit to gradually approach depot
- Client performs near-field rendezvous and docks with depot, remaining docked as long as needed
- Client performs burn to enter elliptical transfer orbit
- Client performs burn to circularize orbit upon reaching GEO

Assumptions:

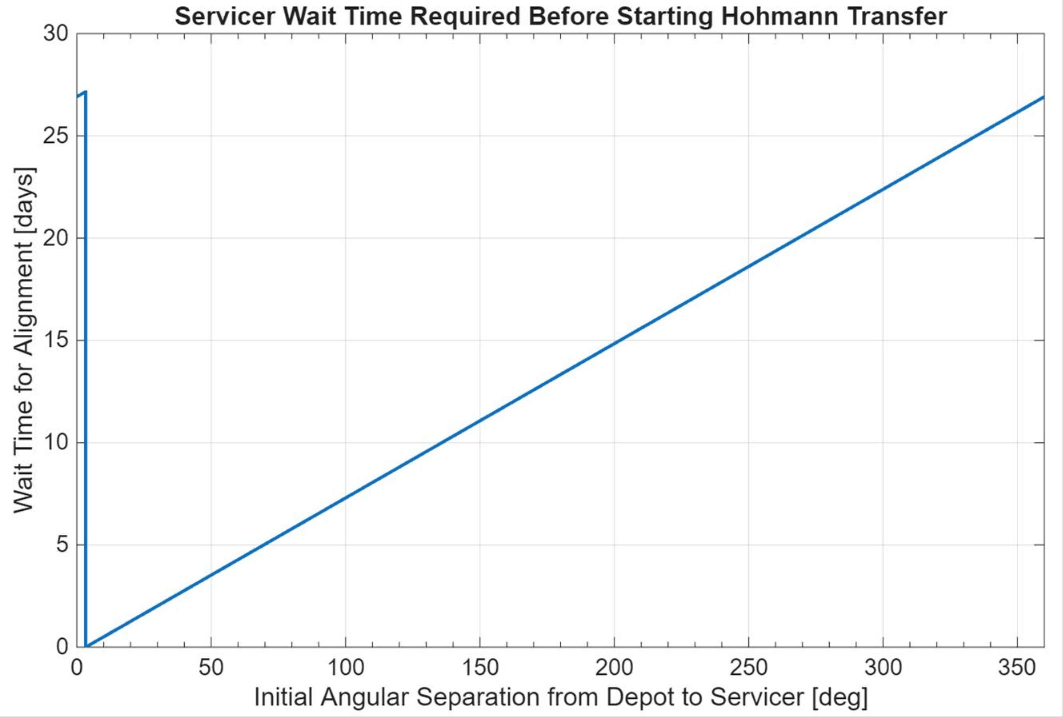
- Client starts in GEO (36,786 km altitude, 0° inclination) and is using chemical propulsion

Client Maneuvers Animation [2.1]



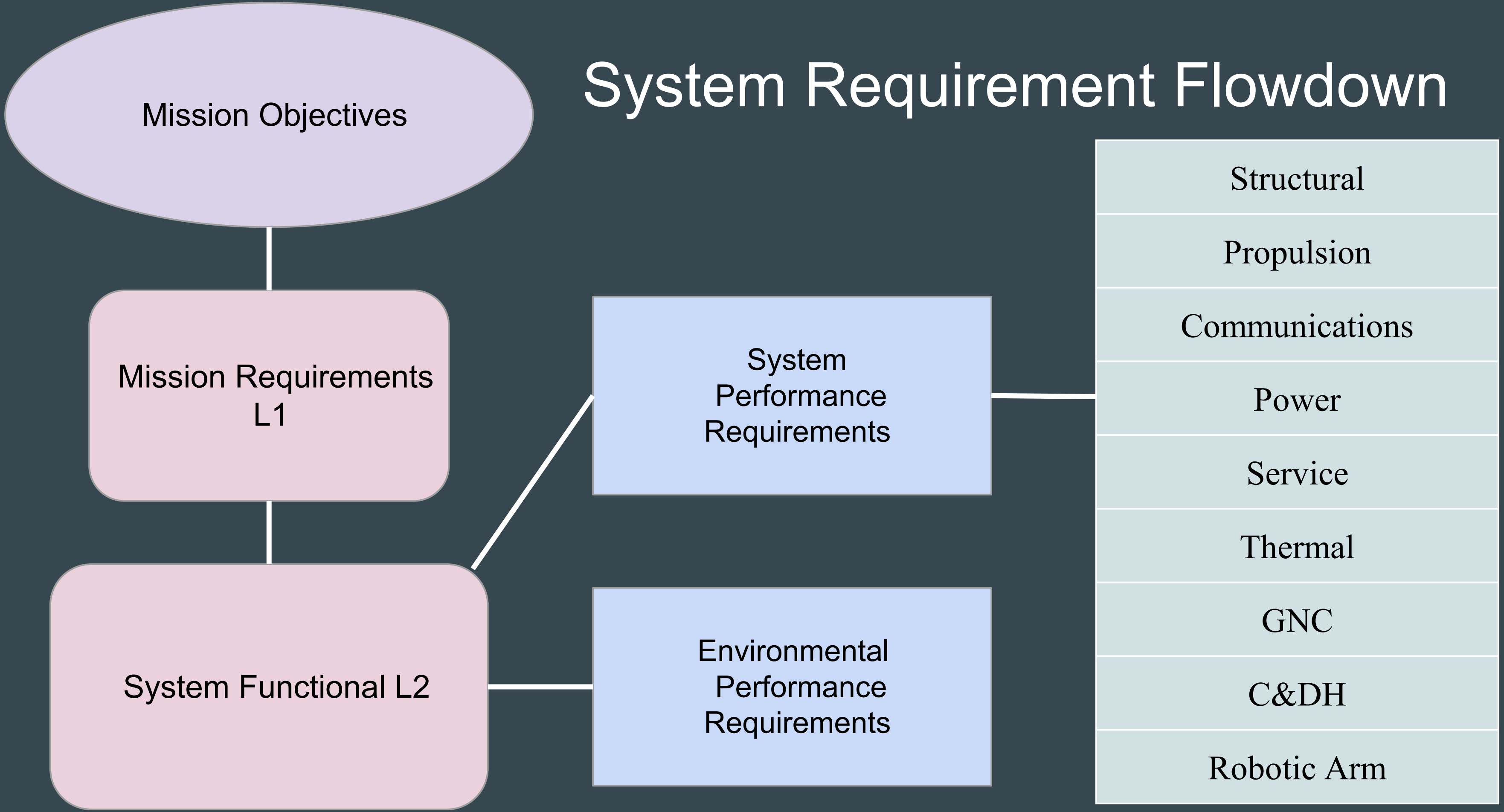
Client Maneuvers Requirements

- Average response time (wait time for alignment plus Hohmann Transfer time): **14.1 days**
- Δv required (one-way): **20 m/s**



System Design

System Requirement Flowdown



Mission Objectives

Mission Requirements L1

System Functional L2

System Performance Requirements

Environmental Performance Requirements

- Structural
- Propulsion
- Communications
- Power
- Service
- Thermal
- GNC
- C&DH
- Robotic Arm

Top Level Mission Requirements

L1-M-03

The spacecraft shall be capable of completing servicing operations in orbit without reliance on human involvement.

L1-M-04

The spacecraft shall be capable of transferring liquid propellant to a client satellite.

L1-M-05

The spacecraft shall be capable of transferring replacement components to a client spacecraft.

L2-M-07

The spacecraft shall be capable of obtaining required replacement components for servicing clients from depot spacecraft that hold replacement components.

L1-M-08

The spacecraft shall be capable of refueling itself from depot spacecraft that contains fuel.

System Functional Requirements

L2-SYS-STRC-01

The spacecraft shall be structurally designed to withstand all mission loads with a 1.4 factor of safety.

L2-SYS-COMM-02

The system shall support bidirectional proximity communications with client satellites

L2-SYS-RA-02

The robotic arm subsystem shall support component transfer operations and shall not be required to perform docking or capture of a client servicer.

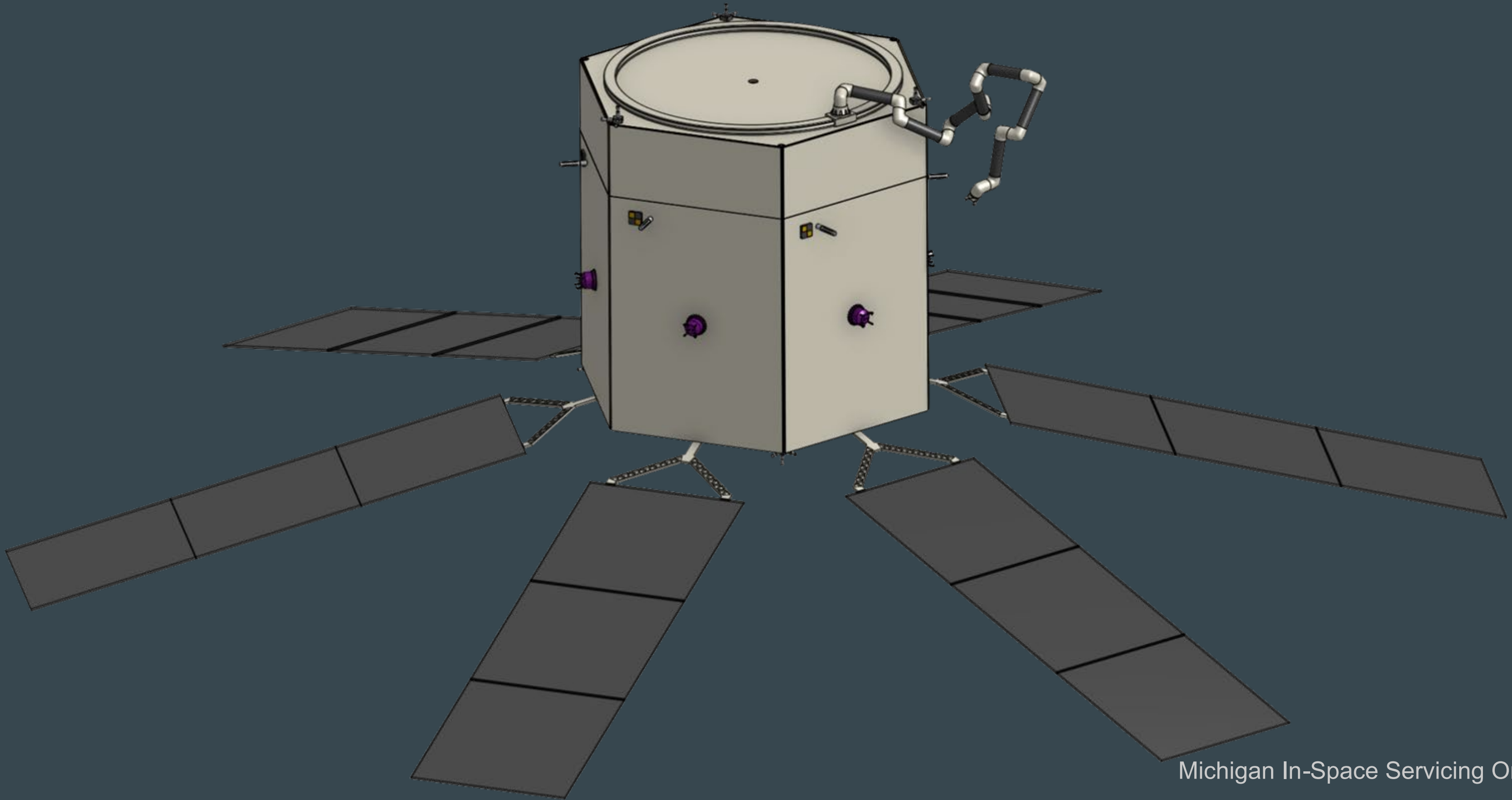
L2-PROP-01

The propulsion subsystem shall store sufficient fuel to meet all Δv requirement with a 20% contingency

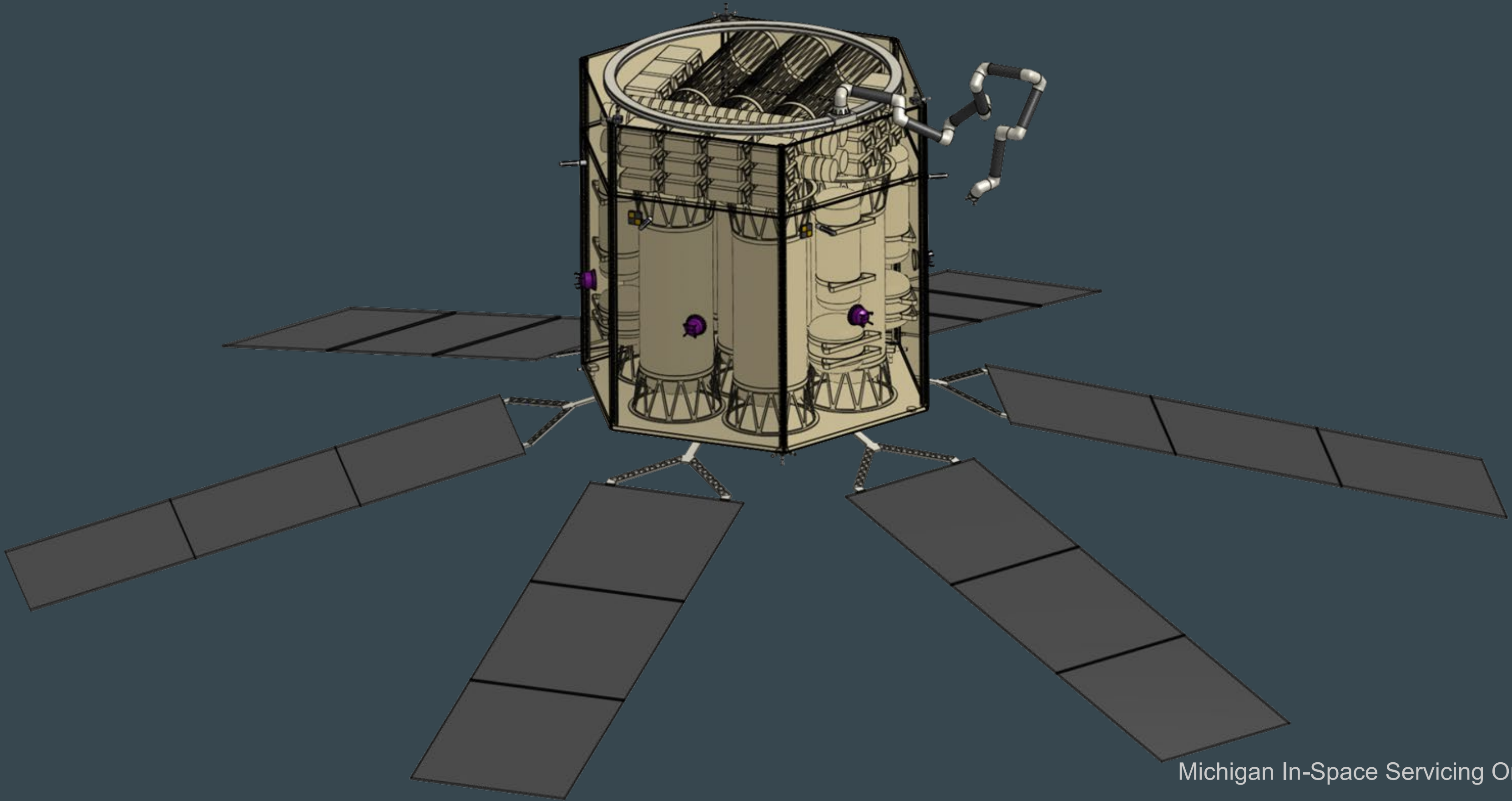
L2-SERV-14

The servicing subsystem shall verify that a module was successfully transferred to a client.

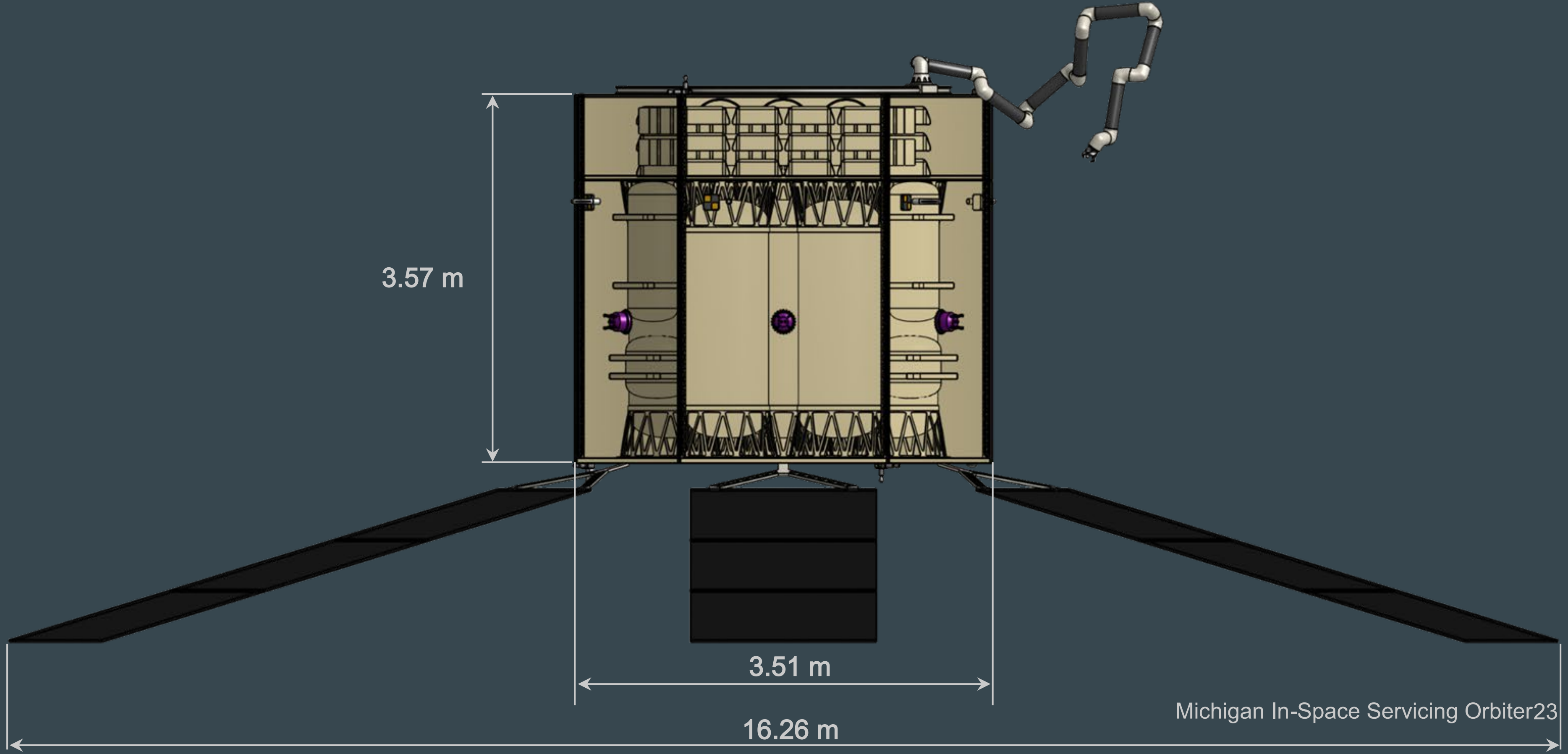
System Design - Depot CAD



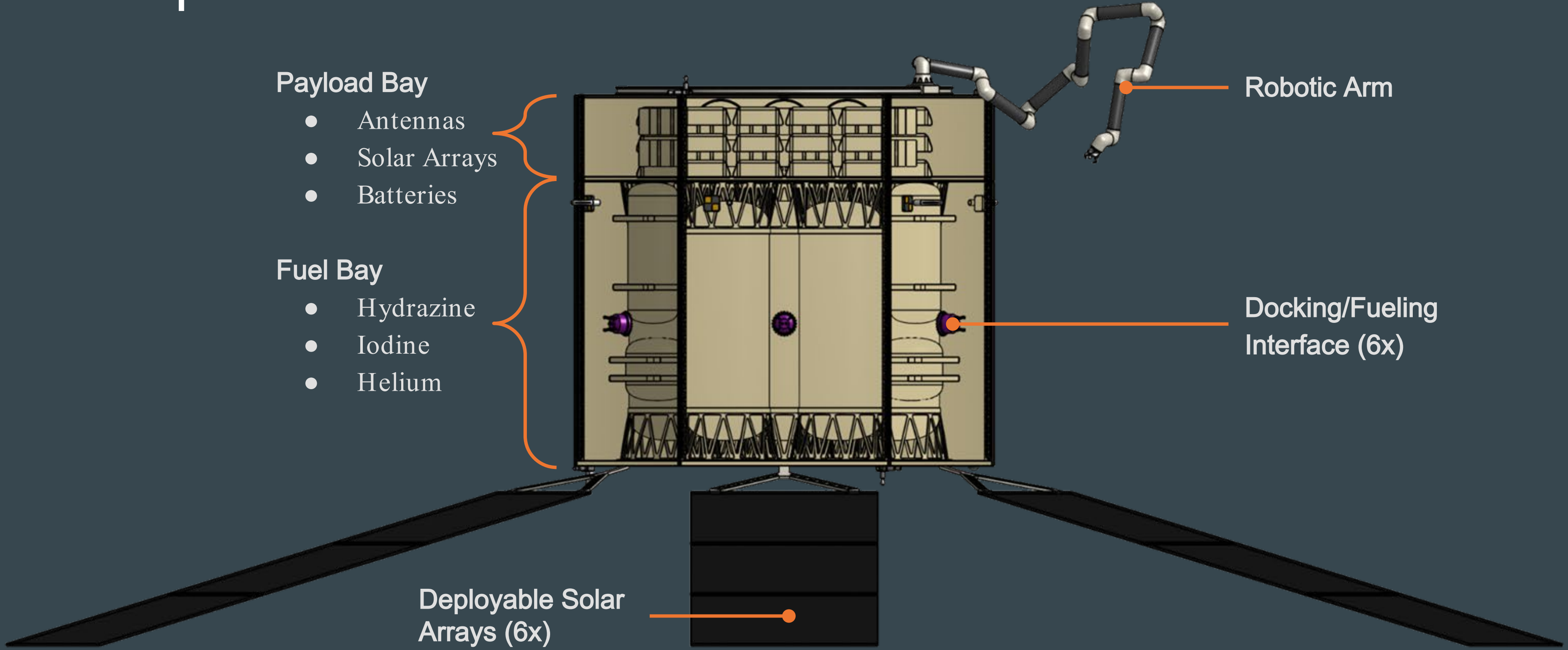
System Design - Depot CAD



General Dimensions



Component Breakdown



Payload Bay

- Antennas
- Solar Arrays
- Batteries

Fuel Bay

- Hydrazine
- Iodine
- Helium

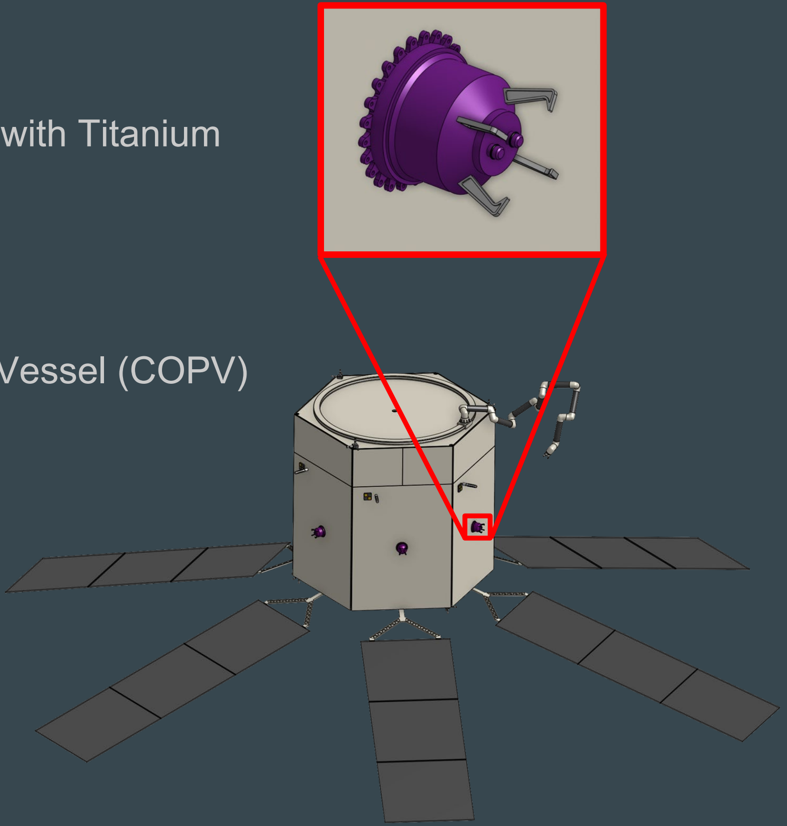
Robotic Arm

Docking/Fueling Interface (6x)

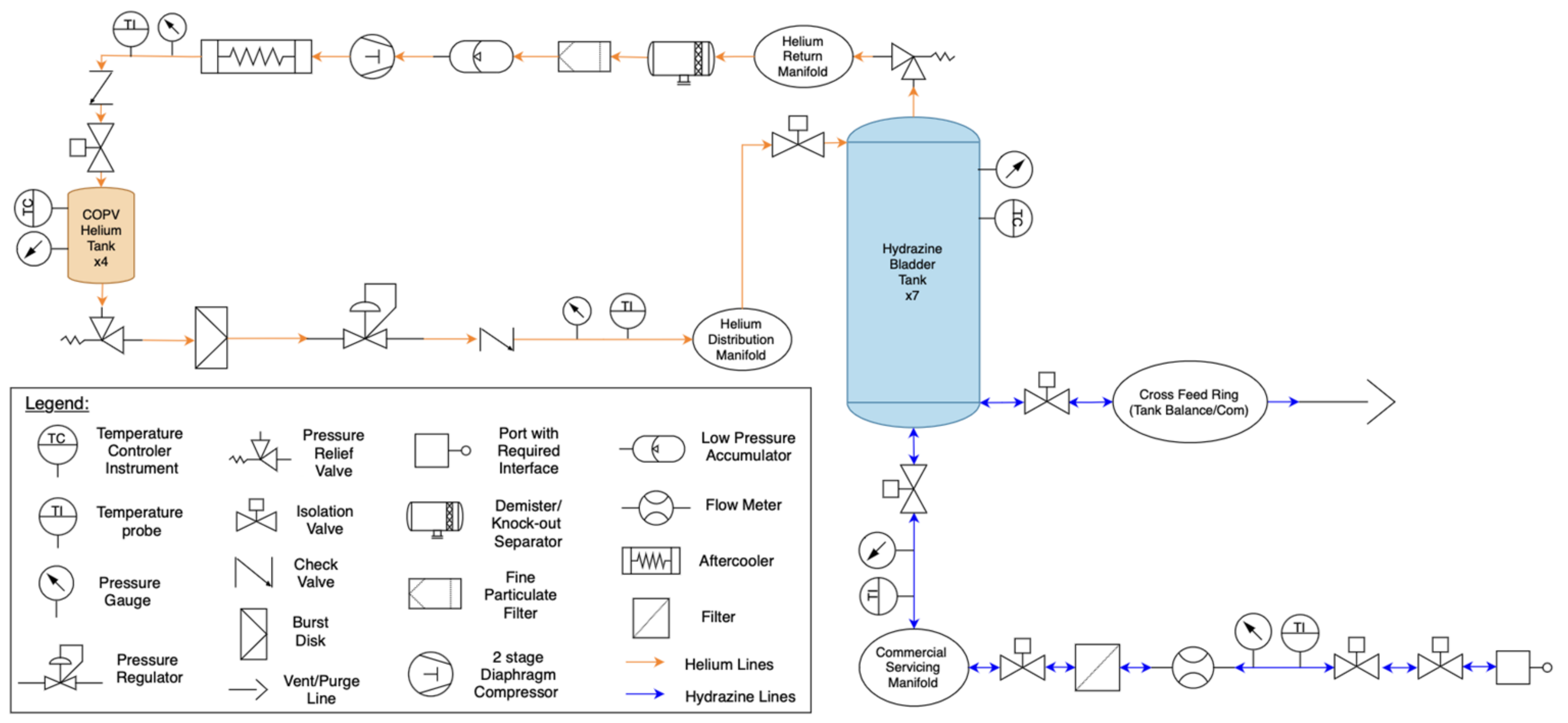
Deployable Solar Arrays (6x)

System Design - Refueling Segment

- **7,000 kg of Hydrazine Propellant**
  - 7 cylindrical bladder tanks (1,089 L each) made with Titanium Alloy (Ti-6Al-4V)
  - Cross-Feed Ring for tank balancing/CoM control
- **40 kg of Helium Pressurant for Feed System**
  - 4 cylindrical Composite Overwrapped Pressure Vessel (COPV) tanks (~230L each) lined with Titanium
  - Closed-loop system
- **PMDs (Propellant Management Devices)**
  - Screen channel and vane-type devices
- **6 Refueling Interfaces**



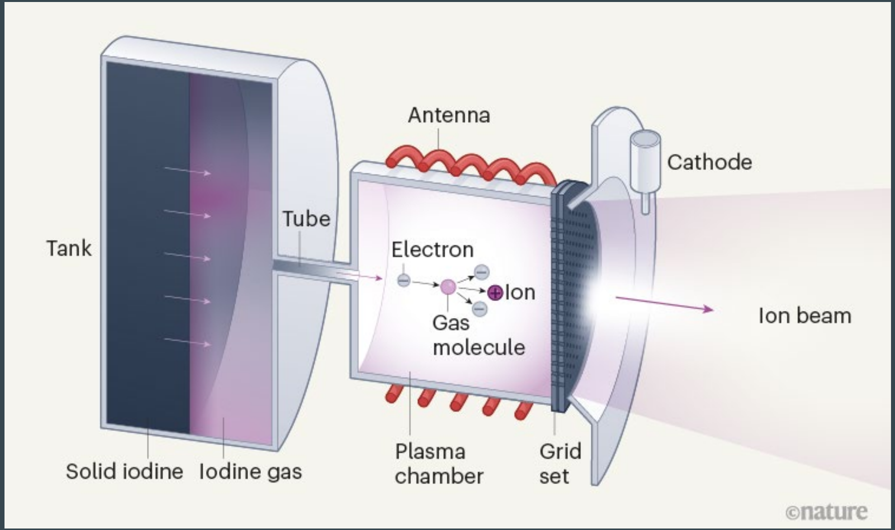
Refueling Manifold



System Design- Propulsion

Propulsion for orbit transfer + station keeping:

- 3,000 kg of Iodine Propellant
  - Tank Specs:
    - 4 cylindrical tanks (~180L each)
    - Nickel alloy (Inconel) with corrosion-resistant internal coating
    - Built-in vaporizer
- 8 Hall Effect Thrusters
  - Thrust: 325mN per thruster
  - Specific Impulse: 2,000 s
  - Efficiency: ~50-60%

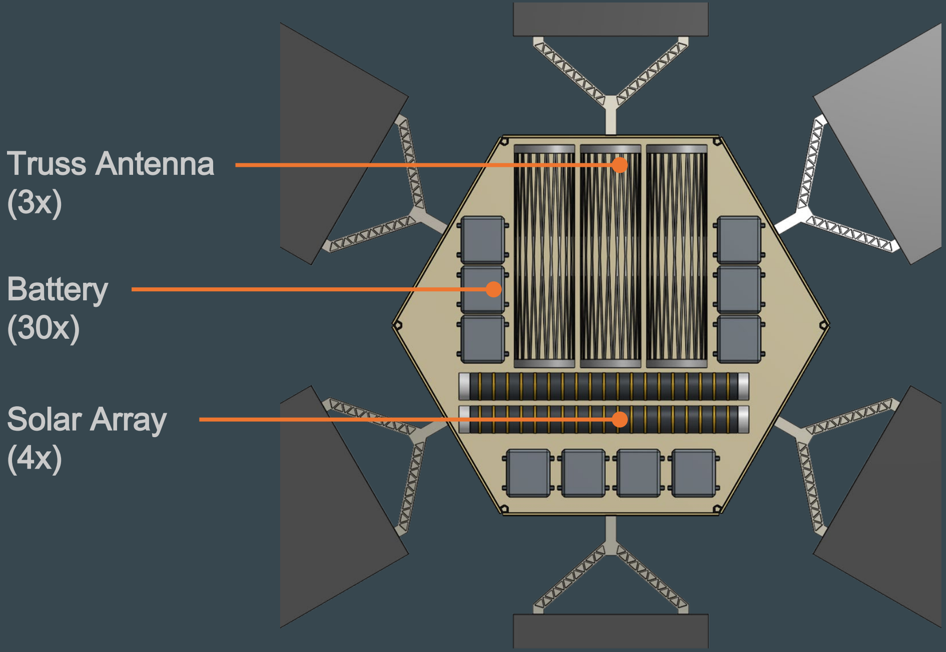


[Nature.com: Iodine powers low-cost engine for satellites]

System Design - Component Storage

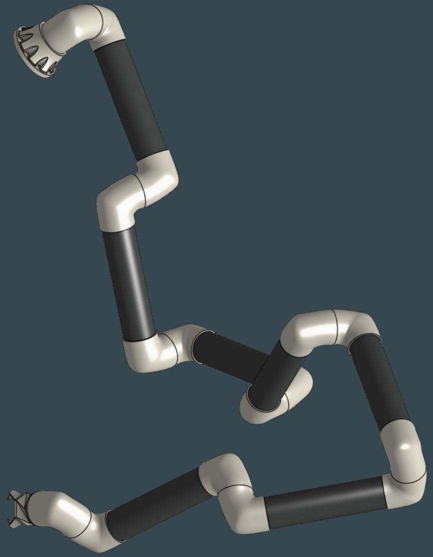
High level analysis deemed the following components suitable to store/deliver:

- Antenna replacement kits (unfurlable mesh reflector canister class)
  - Deployed diameter 12 m, stowed diameter 0.55 m, height 2.1 m, mass 54 kg
- Battery replacement modules
  - Height 0.17 m, length 0.44 m, width 0.40 m, mass 29 kg
- Solar array replacement kits (ROSA-class roll-out wings)
  - Deployed length 12.6 m, stowed diameter 0.25 m, width 2.7 m, mass 43 kg



System Design-Component Handoff Segment

Attribute	Design Choice	Justification
Material	Carbon Fiber Reinforced Polymer	High stiffness-to-weight ratio
Dimensions	0.65 m segment length 7 segments 4.55 m total arm length	From forward/inverse kinematics calculations
Degrees of Freedom	7 DOF	Provides redundancy needed to maneuver around the depot's frame
Stiffness/Payload	Rigid segments	Must be capable of handling 55 kg+ payloads (solar arrays) with high precision
End Effector	Soft, physically malleable gripper	Must distribute forces evenly and prevent damage of delicate components
Drive System	Brushless DC motors at each joint	Enables complex maneuvers



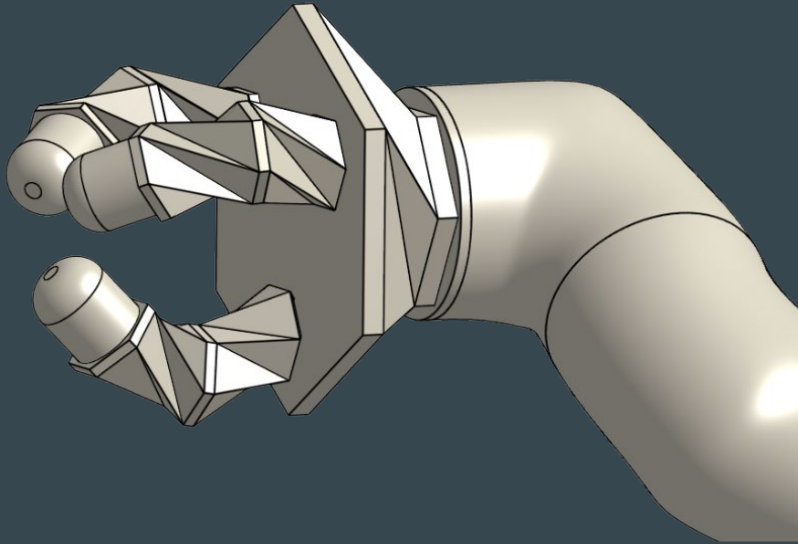
System Design - Component Handoff End Effector

Soft Robotics Structure

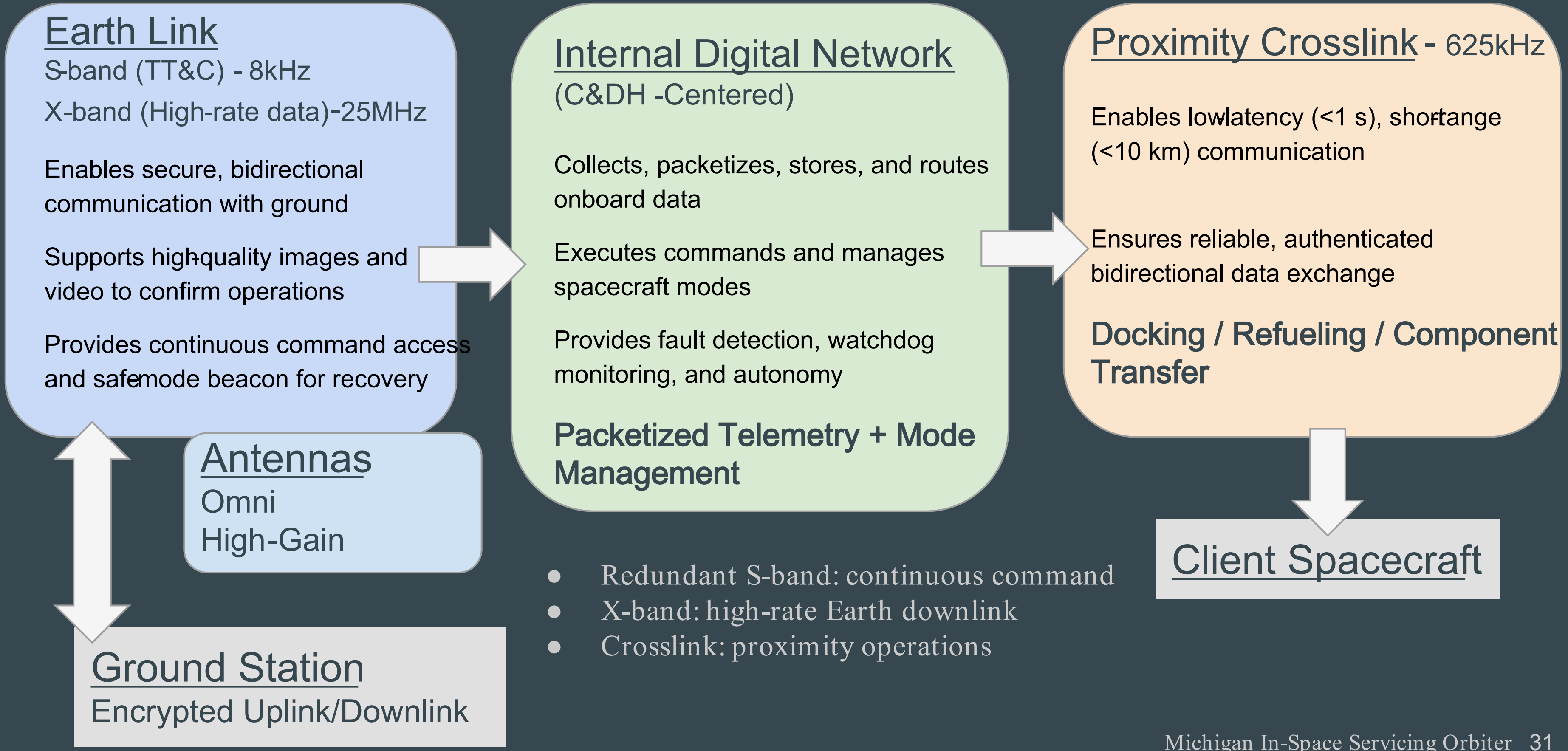
- Kresling origami (Aluminum panels + Kapton hinges)
- Passive compliance for safe grasping

Sensors

- **2x Cameras + 2x LEDs**
  - Depth perception from 1-10 m
  - Identify fiducial markers on components
- **1x Time-of-Flight (ToF) LiDAR unit**
  - Provides mm-accurate distance measurements through lasers
- **3x Short-Range Proximity Laser**
  - Handles final 10 cm of approach
  - Alert grippers to trigger capture sequence
- **1x 6-Axis Force/Torque (F/T) Sensor**
  - Detects exact forces to prevent structural overloading
- **3x Thin-Film Tactile Slip Sensors**
  - Provide micro-haptic feedback by detecting shear forces



System Design - Data Handling & Comms [3.3]



Earth Link

S-band (TT&C) - 8kHz

X-band (High-rate data) - 25MHz

Enables secure, bidirectional communication with ground

Supports high-quality images and video to confirm operations

Provides continuous command access and safe-mode beacon for recovery

Antennas

Omni

High-Gain

Ground Station

Encrypted Uplink/Downlink

Internal Digital Network

(C&DH -Centered)

Collects, packetizes, stores, and routes onboard data

Executes commands and manages spacecraft modes

Provides fault detection, watchdog monitoring, and autonomy

Packetized Telemetry + Mode Management

Proximity Crosslink - 625kHz

Enables low-latency (<1 s), short-range (<10 km) communication

Ensures reliable, authenticated bidirectional data exchange

Docking / Refueling / Component Transfer

Client Spacecraft

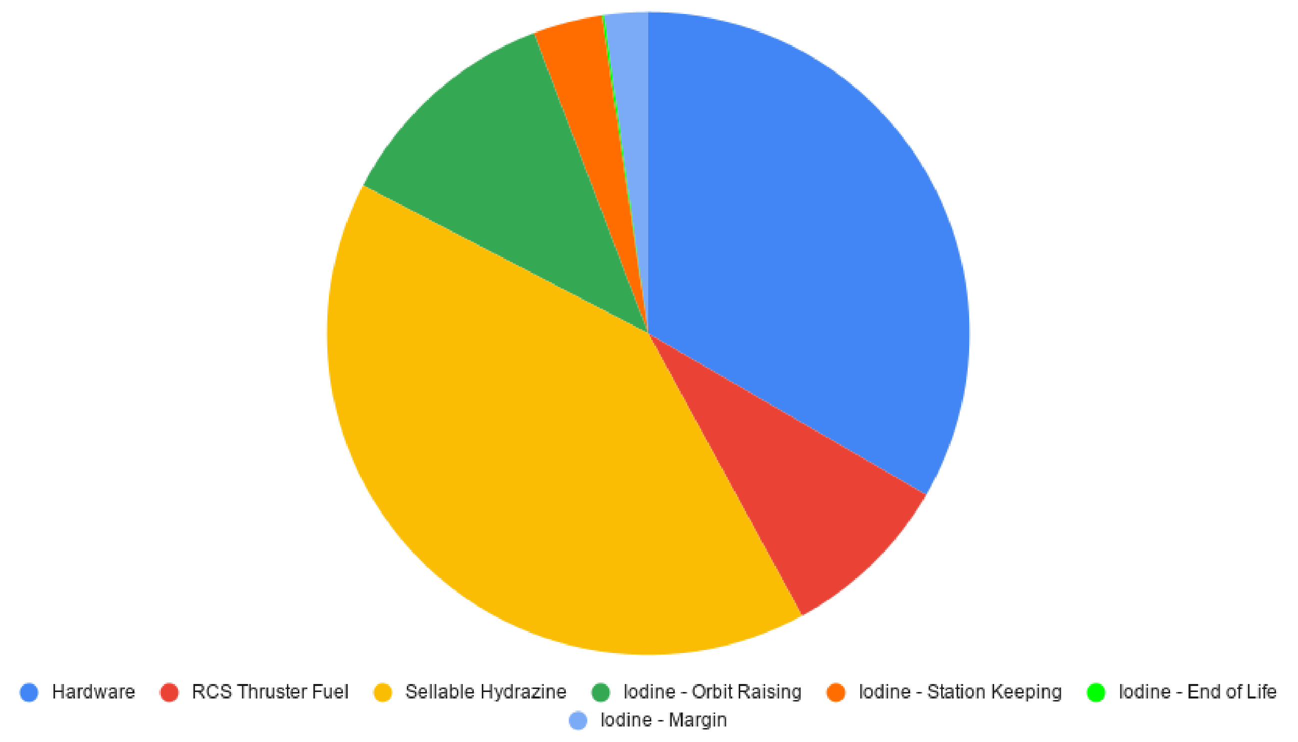
- Redundant S-band: continuous command
- X-band: high-rate Earth downlink
- Crosslink: proximity operations

System Design - Mass Budget

Category	Main Component	Subsystem Mass (kg)
Component Transfer & Interfaces	Robotic Arm	258
Structures	Honeycomb Panels (6x)	1,972
ADCS	RCS Thrusters	235
Propulsion	Propellant + Tanks	17,455
Power	Battery	758
Communications & Avionics	Antennas	48
Thermal	MLI	52

Falcon Heavy Mass to GTO: 26,700 kg	Total System Mass (with 25% margin)	**~26,000 kg**

System Design - Propulsion Budget



System Design - Power Budget

PCL = Power Conversion Loss

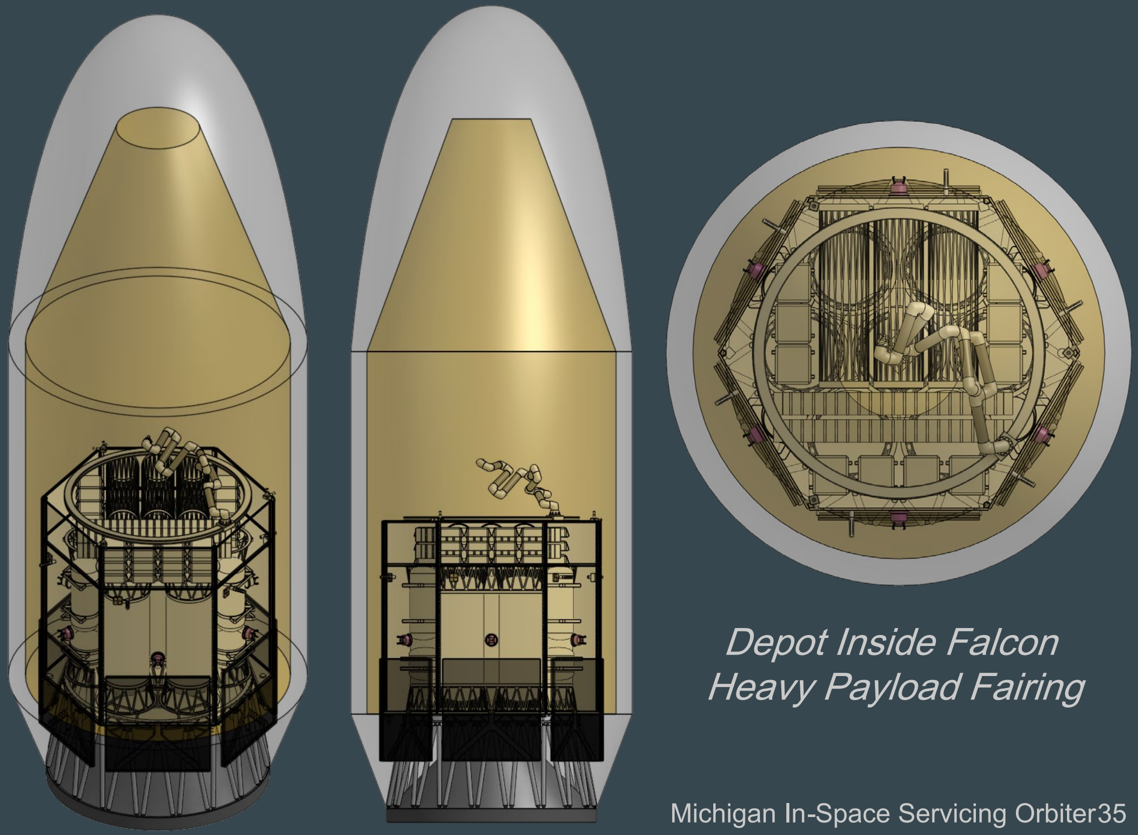
Subsystem		Peak Functionality (W)	Nominal Functions (W)	Safe Mode (W)
Communications	Total	227	157	63
	Minimum After PCL	254	179	71
	Target Power	305	211	85
Propulsion	Total	12,862	7,766	358
	Minimum After PCL	14,155	8,518	401
	Target Power	16,987	10,222	481

Full System Target Power:	**~17,300 W**	**~10,500 W**	**~600 W**

System Design - Launch Environment Considerations

Design features for surviving launch:

- **Centralized load path** through primary structure to payload adapter
- **Stowed configuration for robotic arm** to minimize dynamic loading
- Propellant **tanks structurally supported** to withstand launch loads
- **Symmetric mass distribution** to reduce bending moments



Depot Inside Falcon Heavy Payload Fairing

Engineering Development

Trade Study: Docking Interface

Must-have criteria: has mechanical docking, can transfer fluid, manufactured in US, and has a TRL > 4

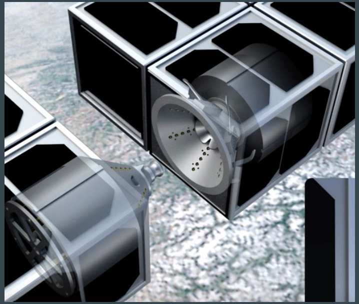
Metrics	TRL	Mass	Volume	Alignment Tolerance	Structural Load Capability	Data Transfer Capability	Non-Cryo Fluid Transfer Capability	Cryo Fluid Transfer Capability	Heritage	Number of partners	In partnership with USSF	Androgynous
Weights (1-10)	10	7	5	9	10	2	9	8	8	6	6	2

Criteria	Concepts						
	GRIP (Orbitfab)	PRM (Northrop Grumman)	FuseBlox (SpaceWorks)	ASPIN (Lockheed Martin)	iSSI (iBOSS)	OneLink (Enduralock)	Multiple Interfaces
Total Score	564	344	614	234	528	494	660
Evaluation	High TRL, has partnerships with USSF and many companies	High TRL, has been demonstrated in space, will likely be high performance	Has lower TRL and heritage, but performs well across most technical metrics	Does not have fuel transfer capability	Has lower TRL and heritage, but performs well across most technical metrics	Very large and heavy, but capable of high structural load	Allows for reaching the most clients, but most expensive

Docking/Refueling Interfaces

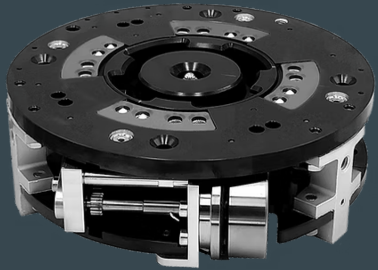
1x FuseBlox - SpaceWorks

1x OneLink - Enduralock

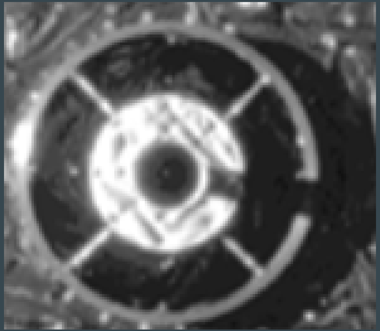


2x GRIP - OrbitFab

1x iSSI - iBoss



1x PRM - Northrop Grumman



Trade Study: Depot Propulsion System

Metrics	Volume Efficiency	Cost	Heritage	Compatibility/ Contamination	Performance Potential	TRL
Weights (1-10)	6	5	5	2	1	1

Criteria	Concepts				
	Xenon	Iodine	Krypton	Argon	Hydrazine
Total Score	136	142	96	100	128
Evaluation	High heritage and performance with excellent Isp, but expensive and requires high-pressure storage	Highest overall score due to high storage density and lower cost while maintaining high performance	Lower cost alternative to xenon but reduced performance (lower Isp and thrust efficiency)	Very low cost and abundant, but significantly lower performance and efficiency	High heritage, but low Isp and low storage density

Trade Study: Robotic Arm

Metrics	TRL	Stiffness/ Payload Capacity	Lifecycle	Grappling Ability	Development Time and Cost	SWap
Weights (1-10)	10	9	8	8	6	4

Criteria	Concepts		
	Custom Soft Arm with Rigid End Effector	Custom Rigid Arm with Soft End Effector	Rigid COTS Arm with Rigid End Effector
Total Score	142	255	242
Evaluation	Exciting concept but no flight heritage; suffers from "wet noodle" oscillations, making 55 kg+ payloa unmanageable; significant radiatio degradation risk over 15 years	Optimal balance of safety and stability; sof end effector prevents payload crushing an rigid structure provides high-load stability for 55 kg+ payloads; 15+ year mission durability	High flight heritage, but high risk of crushing delicate payloads du to no physical give in the rigid gripper

Engineering Development Risk Assessment [3.2]

	Severity				
		2	3	4	5
Probability + Detectability	6			R-CDH-07	
	7			R-COMM-09 R-GNC-02 R-GNC-09	R-PROP-03 R-RAD-02
	8		R-GNC-07 R-GNC-16 R-PROP-10 R-PWE-09 R-RAD-03		
	9		R-SVC-11 R-STRC-04		

Major Risks and Mitigations [3.2]

Risk ID	Description	Mitigation
R-PROP-03	Propellant leak or contamination during refueling	Dual isolation valves; leak-check sequencing before transfer; inline filtration; autonomous abort capability upon abnormal pressure or flow detection
R-RAD-02	Radiation-induced degradation of servicing components reduces operational reliability	Rad-tolerant electronics and shielding for critical subsystems; fault detection and reconfiguration capability after upsets
R-SVG-11	Verification of module transfer fails to detect unsuccessful handoff	Incorporate redundant confirmation sensors and require positive verification before arm release or departure maneuvers.
R-STR-04	Long-term material degradation from thermal cycling reduces structural strength	Use materials with demonstrated resistance to thermal cycling and UV exposure; and perform accelerated life testing to validate structural margins over mission duration.

Engineering Development - Interface Control

Client Compatibility:

- Class A: Docking + Refueling + Handoff
- Class B: Docking + Refueling
- Class C: Docking + Handoff

Docking Interface (Client must-haves):

- Compatible mechanical interface
- Structural capacity for docking loads
- Clearance compatible with MISO keep-out zones
- Cooperative relative navigation

Refueling Interface:

- Fluid transfer capability + compatible coupling
- Isolation valve + tank telemetry
- Enabled post-docking only

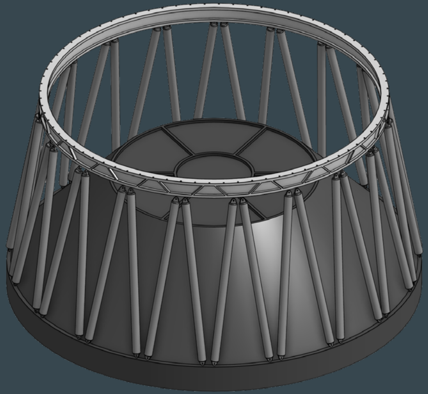
Robotic Interface:

- Defined install interface (mechanical/electrical)
- Clearance envelope for robotic arm approach
- Installation verification feedback

Development Plan

Path to PDR [2.3]

- Confirm launch vehicle integration: SpaceX's Falcon Heavy offers a payload attach fitting (PAF) compatible with MISO which is included in our CAD model
- Perform structural analysis and validate load cases
- Finalize keep-out zones and operational constraints into a client Interface Control Document (ICD)
- Design resupply spacecraft
- Risk burndown



Falcon Heavy
PAF

Paper [5.2]

We plan to submit our technical paper to the 2026 SciTech Forum. The paper includes areas which were not covered in the presentation, including

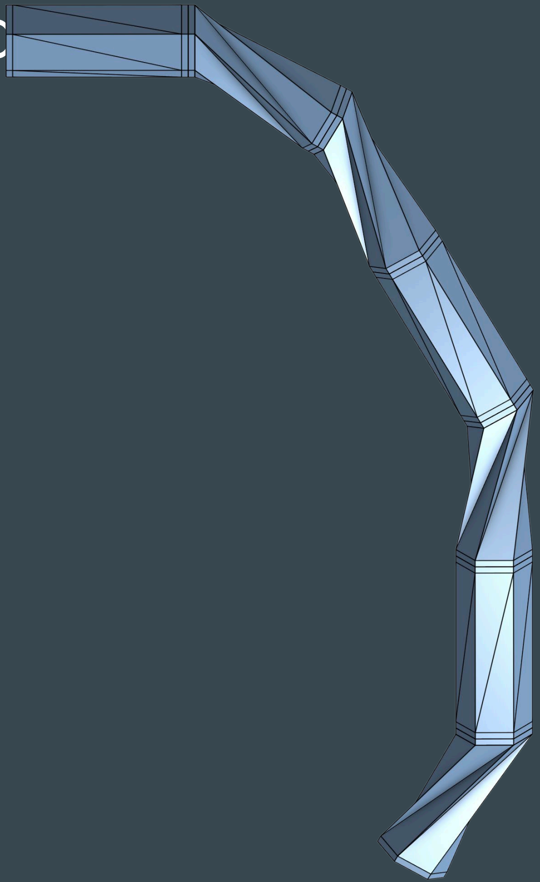
- Thermal/Radiation analysis
- Depot altitude selection justification
- Interface control strategy

Key parameters of the paper:

- Abstract Length: 212 words
- Paper Length: 20 pages
- Number of references: 12

Lessons Learned

Most Innovative Concepts Considere



- Dual-use depot: combining refueling with robotic component handoff
- Modular servicing architecture: swapping between different end-effectors to enable a multitude of servicing operations
- Soft robotic arm: utilize Kresling geometry for an ultra-maneuverable robotic manipulator

Most Important Technology Gaps [4.2]

- Large-scale iodine electric propulsion
    - Iodine as an electric propellant has been demonstrated in space, but only for SmallSats
- Closed-loop hydrazine tank pressurization
    - Necessary for large scale hydrazine refueling systems, but has not been tested in space
- Compact replacement modules which can be easily integrated with spacecraft
    - Rolled-up solar arrays, battery modules, and antenna modules currently lack standardized interfaces
- Soft robotics
    - Limited testing, still not space rated

Biggest Challenges Encountered [4.3]

- Orbital insertion of such a high mass system
  - Required high transfer time, reliance on iodine propellant, and resupply missions to reduce initial mass
- Robotic arm development
  - Balancing the use of novel soft robotics with the need for sufficient structural stiffness to support heavy components
  - Adapting textbook forward and inverse kinematic equations to determine the required arm reach
- Feasible business case
  - Balancing development cost with revenue
  - Attracting customers with reasonable prices

Conclusion

Mission Capability:

- Demonstrates a fully integrated orbital depot enabling propellant storage, transfer, docking, and robotic component handoff within a single platform.

Innovation:

- Combines refueling and modular component handoff with standardized interfaces, enabling reusable, upgradeable spacecraft architectures.

Impact:

- Shifts space operations from single-use missions to serviceable, scalable infrastructure—reducing cost and extending mission lifetimes.

Why It Matters:

- Establishes the foundation for a sustainable in-space logistics network, unlocking more ambitious, long-duration missions beyond Earth.

Thank you!

Questions?

Backup Slides

Engineering Development - Thermal Analysis Setup

- 300-node thermal model and analysis using Thermal Desktop
- Setup:
  - Expected orbit with DITL power use (160 W)
  - Assumptions:
    - Depot is covered in silver MLI, expect +z face (radiator surface)
    - -z face facing towards sun, bbq roll spin along z-axis
- Temperature sensitive components
  - Interfaces
  - Hydrazine and iodine propellant tanks
  - Battery (assumed Ni-H2)
  - Robotic Arm (assumed covered in MLI → negligible radiative heat loss)

Engineering Development - Thermal Analysis Results

- Component temperature margins

Component	Min. Op. Temp. (°C)	Max. Op. Temp (°C)	Min Margin (°C)	Min Temp (°C)	Max Temp (°C)	Max Margin (°C)
Interface	-35	60	52	17	20.1	39.9
Hydrazine Tanks	10	40	10.4	20.4	24.1	15.9
Iodine Tanks	20	50	11.1	31.1	31.5	18.5
Battery (Ni-H2)	-25	30	33.5	8.5	9.3	20.7
Robotic Arm	-	-	-	8.3	9.2	-

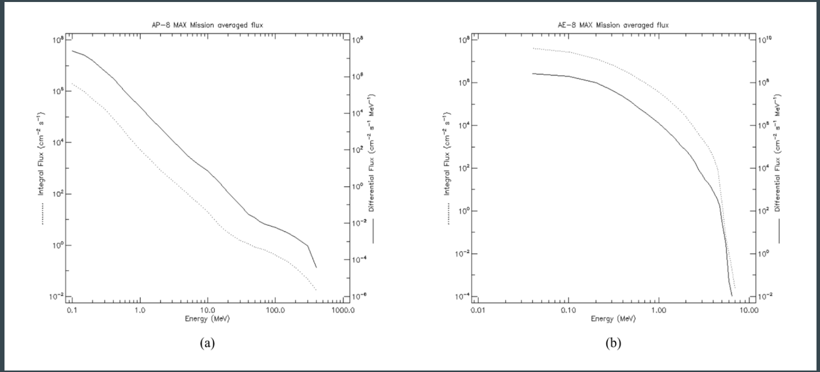
Engineering Development Thermal Analysis Results

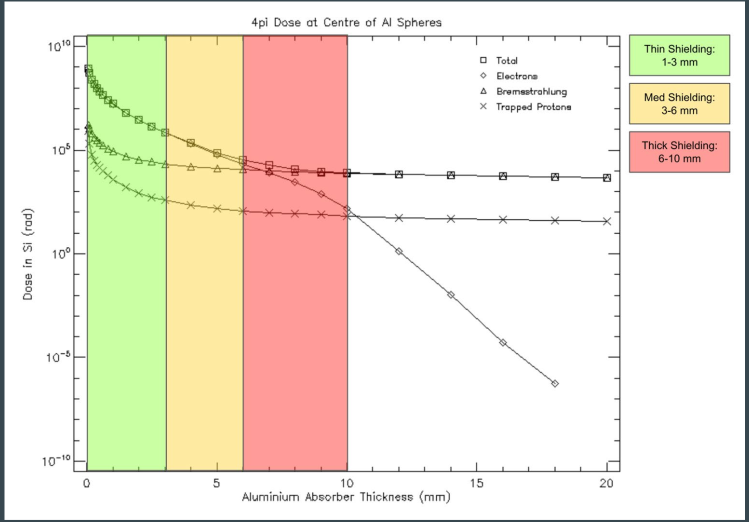
- Heater duty cycles
- High relevative power consumption, suggests mitigation strategies should be explored if work were continued

Heater	Total Energy (J)	Average Power (W)	Duty Cycle (%)	Max Power (W)
Hydrazine 1 - 7	0	0	0	0
Iodine 1	2,713,530	15.7	100	21.7
Iodine 2	2,787,800	16.2	100	22.2
Iodine 3	2,577,250	15.0	100	20.9
Iodine 4	2,717,360	15.8	100	21.7
Total	**10,795,940**	**62.6**	**-**	**115.5**

Engineering Development - Radiation Analysis (SPENVIS)

- Radiation environment
    - 15 year radiation exposure
    - Outer Van Allen radiation belt
    - Relativistic electrons dominate radiation environment (0.04-2MeV)
    - Few high energy trapped protons
- Aluminum spot shielding thickness
    - Med Shielding: 3-6 mm
    - Thick Shielding: 6-10 mm



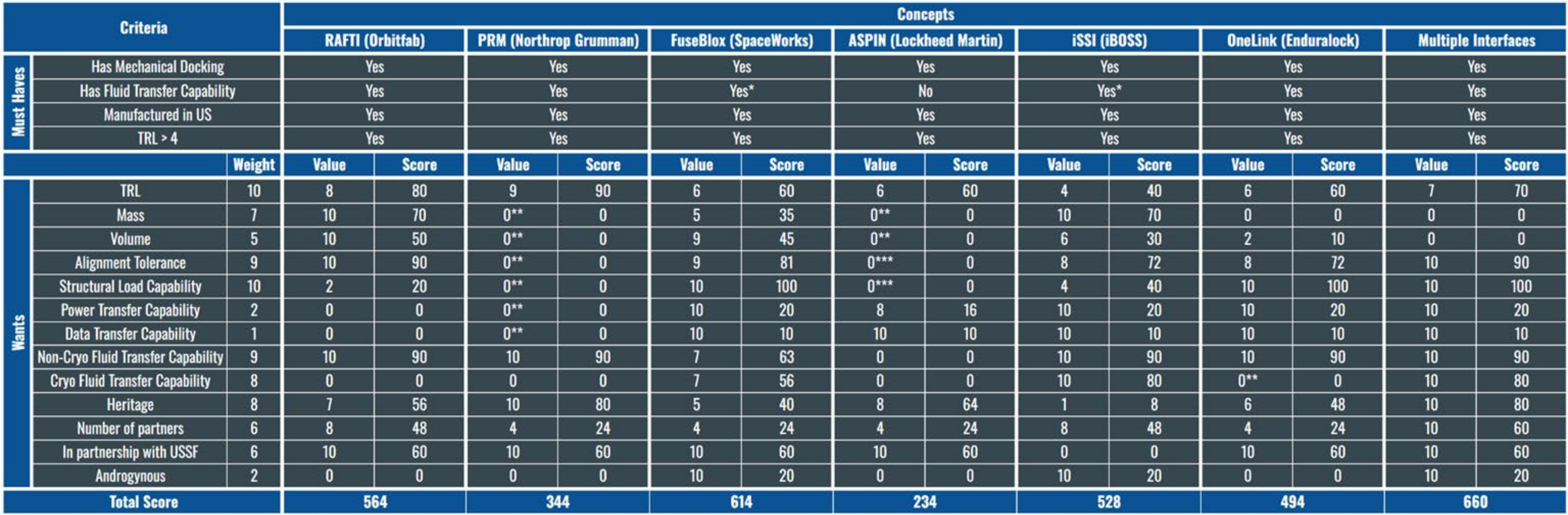


Detailed System Design – Refueling Segment

- **Propellant : Hydrazine – 15,000 kg**
    - Tank Specs: 7 Cylindrical bladder tank
        - Material: Titanium Alloy (Ti-6Al-4V)
        - Size: 2,300L each
        - Operating Pressure (MEOP): 15–25 bar
        - Proof Pressure: ~1.5× MEOP (~35–40 bar)
        - Burst Pressure: ~2× MEOP (~50 bar)
        - Multi layer insulated (MLI) for thermal protection and active thermal control to prevent boil-off
    - Cross-Feed Ring for tank balancing/ CoM control
- **Feed System: Helium Pressurized ~400kg**
    - Tank Specs: 4 Cylindrical Composite Overwrapped Pressure Vessel (COPV) tanks
        - Material: Titanium Lined with Carbon fiber/epoxy overlay
        - Size: ~400L each
        - Storage pressure: ~250–350 bar
        - Regulated output: 15–25 bar
- **PMDs (Propellant Management Devices):**
    - Screen channel and vane-type devices
    - Capillary-driven liquid transport

Trade Study: Docking Interface

Using multiple interfaces were selected for the concept.



Criteria			Concepts													
			RAFTI (Orbitfab)		PRM (Northrop Grumman)		FuseBlox (SpaceWorks)		ASPIN (Lockheed Martin)		iSSI (iBOSS)		OneLink (Enduralock)		Multiple Interfaces	
Must Haves	Has Mechanical Docking		Yes		Yes		Yes		Yes		Yes		Yes		Yes	
	Has Fluid Transfer Capability		Yes		Yes		Yes*		No		Yes*		Yes		Yes	
	Manufactured in US		Yes		Yes		Yes		Yes		Yes		Yes		Yes	
	TRL > 4		Yes		Yes		Yes		Yes		Yes		Yes		Yes	
		Weight	Value	Score	Value	Score	Value	Score	Value	Score	Value	Score	Value	Score	Value	Score
Wants	TRL	10	8	80	9	90	6	60	6	60	4	40	6	60	7	70
	Mass	7	10	70	0**	0	5	35	0**	0	10	70	0	0	0	0
	Volume	5	10	50	0**	0	9	45	0**	0	6	30	2	10	0	0
	Alignment Tolerance	9	10	90	0**	0	9	81	0***	0	8	72	8	72	10	90
	Structural Load Capability	10	2	20	0**	0	10	100	0***	0	4	40	10	100	10	100
	Power Transfer Capability	2	0	0	0**	0	10	20	8	16	10	20	10	20	10	20
	Data Transfer Capability	1	0	0	0**	0	10	10	10	10	10	10	10	10	10	10
	Non-Cryo Fluid Transfer Capability	9	10	90	10	90	7	63	0	0	10	90	10	90	10	90
	Cryo Fluid Transfer Capability	8	0	0	0	0	7	56	0	0	10	80	0**	0	10	80
	Heritage	8	7	56	10	80	5	40	8	64	1	8	6	48	10	80
	Number of partners	6	8	48	4	24	4	24	4	24	8	48	4	24	10	60
	In partnership with USSF	6	10	60	10	60	10	60	10	60	0	0	10	60	10	60
	Androgynous	2	0	0	0	0	10	20	0	0	10	20	0	0	10	20
Total Score			564		344		614		234		528		494		660	

* Requires additional add-on module

** Not disclosed or proprietary

*** TBD

Trade Study: Depot Propulsion System

Metric	Weight	Xenon		Iodine		Krypton		Argon		Hydrazine	
Volume Efficiency	6	6	~1.6 kg/L, gas	10	4.93 kg/L, solid	2	~0.8 kg/L, gas	2	~0.4 kg/L, gas	4	1.004 kg/L, liquid
Cost	5	2	$2,500–3,500 /kg	8	$60–80 /kg	6	$300–800 /kg	10	$0.5–5 /kg	8	$74.50 /kg
Popular/ GEO Usage	5	10	Industry standard	4	Emerging use	4	Niche use	2	Experimental use	8	Legacy standard
Compatibility/Contamination	2	10	Inert, minimal contamination	4	Reactive, contamination risk	10	Inert, low contamination	10	Inert, low contamination	6	Toxic, handling risk
Performance Potential	1	10	High specific impulse, efficient	8	Near-xenon performance	6	Lower efficiency than xenon	4	Low efficiency, power limited	2	Low specific impulse
TRL	1	10	TRL 9	6	TRL 6–7	8	TRL 8–9	4	TRL 5–6	10	TRL 9
Total Score		**136**		**142**		**96**		**100**		**128**	

Trade Study: Robotic Arm System

Metric	Weight	Custom Soft Arm with Rigid End Effector		Custom Rigid Arm with Soft End Effector		Rigid COTS Arm with Rigid End Effector	
TRL	10	2	Experimental (1-2)	5	Developing (3-4)	9	Flight Proven (8-9)
Novelty	10	10	Patentable; Tendon-driven Kresling Origami structure never done before in a depot	7	Soft robotic end effector with a gecko adhesive is up and coming	1	“Black Box” technology with no customization possible
Grappling Ability	7.5	4	Poor; rigid claw on a soft arm creates damaging "point loads" on components	9	Superior safety; soft effector conforms to payloads to eliminate crushing risks	3	High risk; rigid contact relies on softwar loops that can fail during signal lag
SWaP	6	9	Elite; 10:1 compression ratio allows for ultr low stowed volume and mass (<15kg)	6	Moderate; 35-50 kg mass is a calculated trade-off for required arm stiffness	4	Sub optimal; over-engineered for generi use, leading to excess mass and volume
Development Time and Cost	6	3	High risk 5-7+ year R&D timeline with significant testing uncertainty	6	Standard 3-5 year cycle for aerospa design and structural analysis	9	Rapid integration; 1-2 year lead time with no internal R&D required
Stiffness/Payload Capacity	4	2	Fails criteria; suffers from "wet noodle" oscillations when moving heavy payloads	5	High-load stability; specifically engineered to handle 200 kg+ payloads at 4.55m	7	Stable, but operational envelopes are restricted by vendor-set torque limits
Lifecycle	4	3	Low durability; polymers degrade rapidly under heavy radiation and thermal swings	8	Space-grade Aluminum/CFRP provides high resistance to 15+ yea thermal cycling	9	Guaranteed 10-15 year lifespan backed vendor flight data
Environmental Impact	2.5	4	Moderate risk; soft polymers may exceed standard outgassing limits	10	Minimal risk; uses verified material with negligible outgassing	10	Fully qualified to meet strict NASA/ESA outgassing standards
Total Score		**252**		**336.5**		**289.5**	

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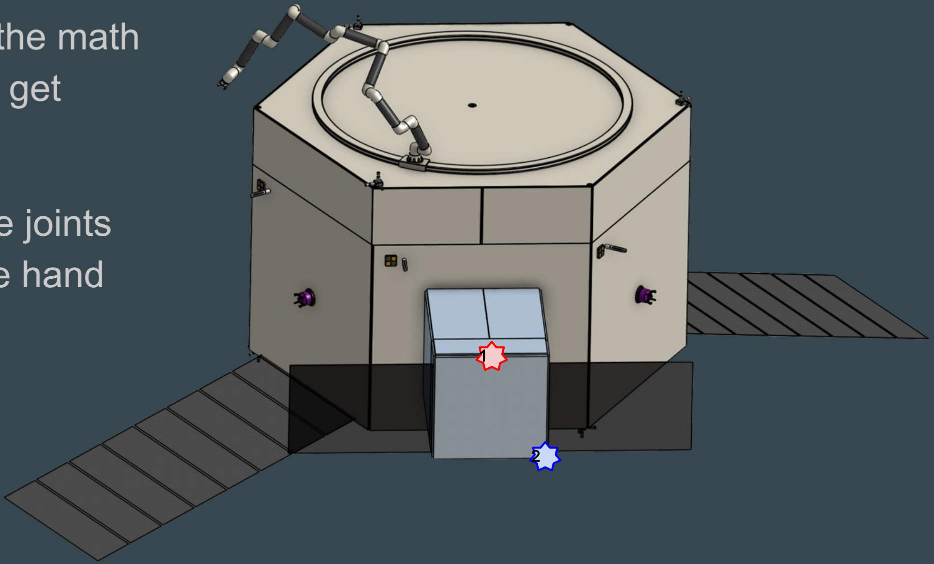
Forward/Inverse Calculations Setup

Inverse Kinematics (IK)- when you know where you want the hand to go (your Target 1 and Target 2), and the math figures out how each of the joints need to bend to get there

Forward Kinematics (FK)- when you know how the joints are bent, and the math confirms exactly where the hand ended up

2 Target locations the robotic arm needs to reach

- Target 1 Straight Distance
- Target 2:Bottom Right Corner (Worst-Case Scenario)



Robotic Arm Calculation Results

Straight-line distance from circular rail to corner: 4.30 m

Required arm length (with 5% buffer): 4.52 m

N = 7 segments (Total Length = 4.55 m)

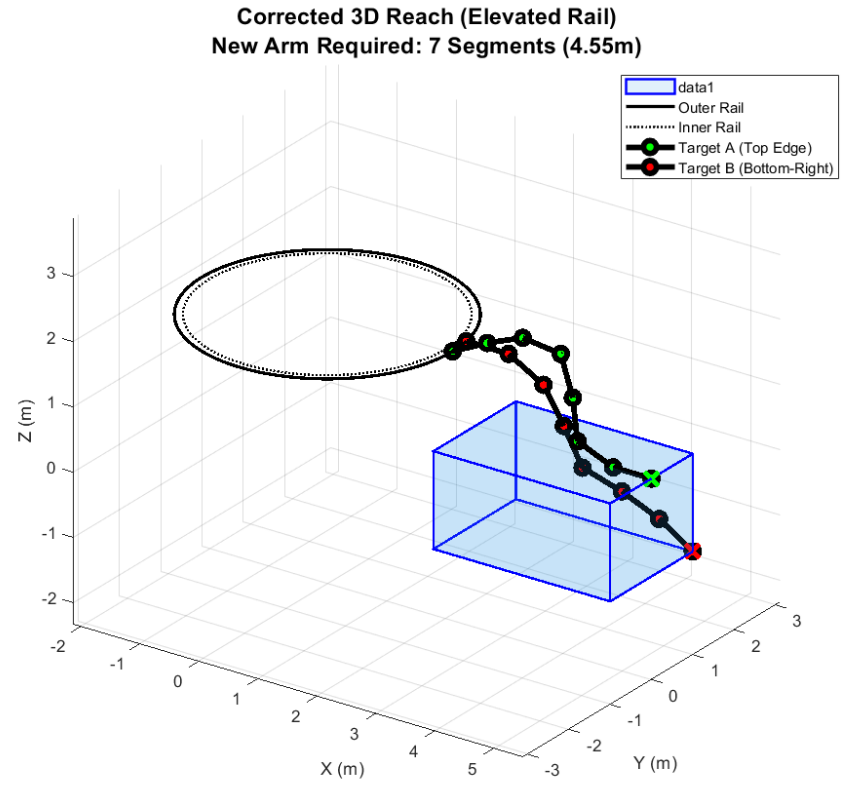
Servicer Dimensions: 3m x 2m x 1.5 m

- Target A: Iterations to converge: 33
- Target B: Iterations to converge: 213

Shows that robotic arm is highly dexterous. Even in confined, worst-case scenarios, the arm is capable of finding a valid configuration

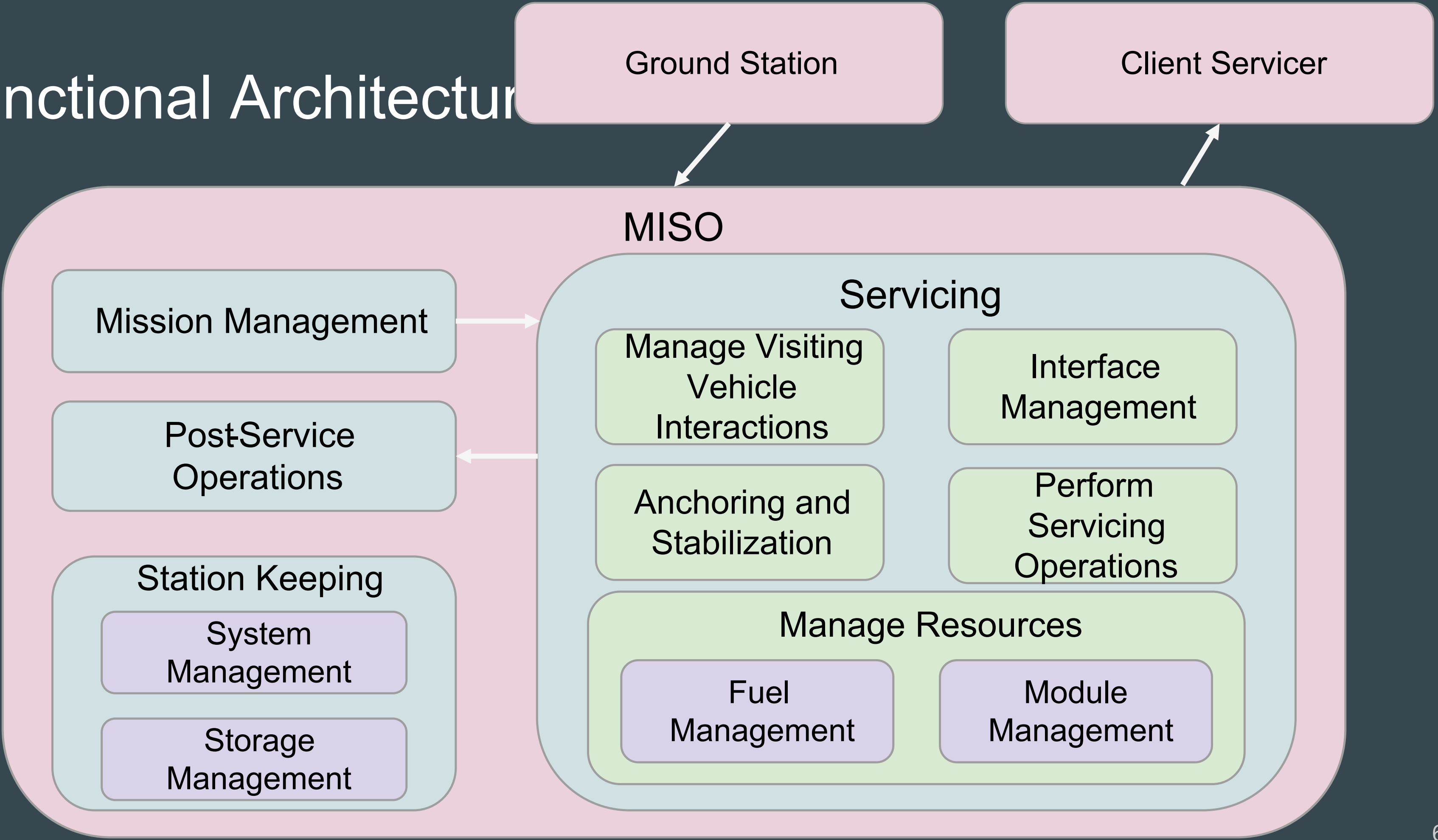
- Target A: Final Tip Error: 0.000979 m
- Target B: Final Tip Error: 0.000948 m

Can position arm less than a mm away from target position



System Architecture

Functional Architectur



Ground Station

Client Servicer

MISO

Mission Management

Post-Service Operations

Station Keeping

System Management

Storage Management

Servicing

Manage Visiting Vehicle Interactions

Interface Management

Anchoring and Stabilization

Perform Servicing Operations

Manage Resources

Fuel Management

Module Management

Logical Architecture

Service Management

- Vehicle Needs Assessment
- Service Task Planning
- Module Part Transfer
- Refueling Operations
- Service Verification

Resource Management

- Fuel Management
- Module & Part Management

Station Keeping

- Power & Thermal Control
- Robotics Health/ Calibration
- Docking Port Readiness
- Fault Detection Isolation & Recovery
- Ground Telemetry

Mission Management

Safety & Mission Planning

- Client Coordination
- Mission Mode Selection
- Mission Assessment
- Safety Assessment
- Rendezvous Authorization
- Abort & Safe-State Control

Interface Validation

- Vehicle Identification
- Compatibility Check
- Position Estimation
- Docking Validation

Customer Vehicle Management

- Relative Navigation
- SpacialZone Management
- Docking Port Allocation
- Approach Window Coordination

Capture/Release

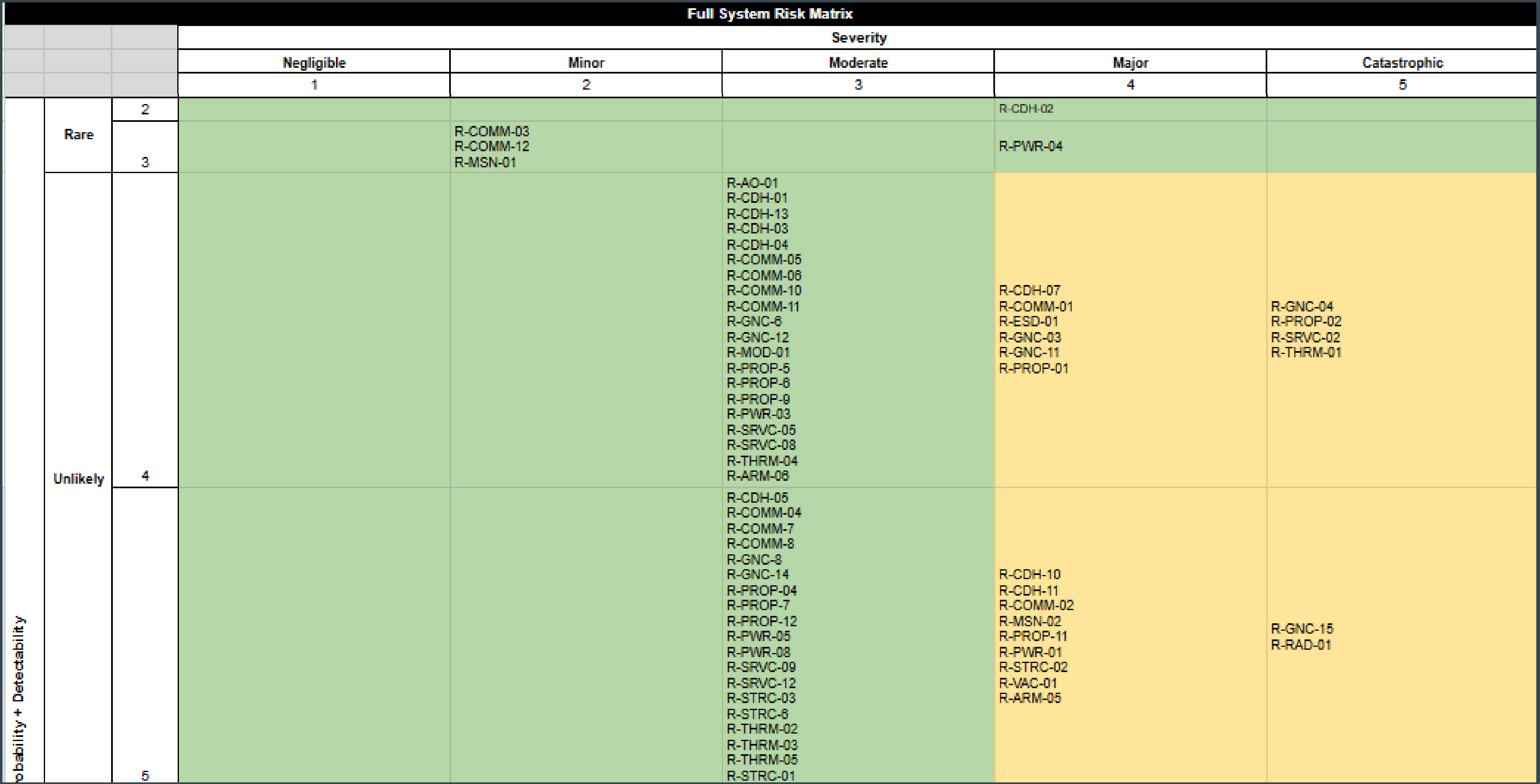
Vehicle Capture

- Pre-Positioning
- Motion Damping
- Initial Contact
- Anchoring
- Engagement
- Load Stabilization

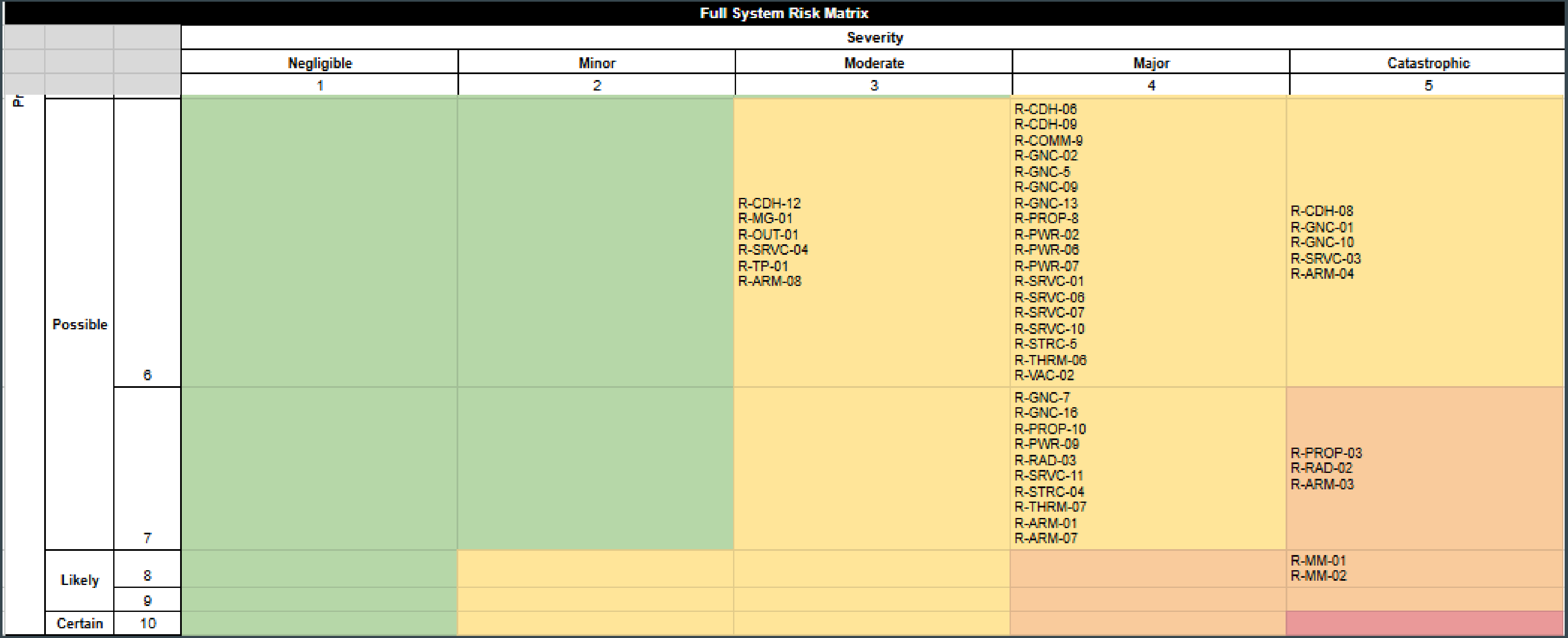
Release & Departure

- Servicing Reset
- Anchor
- Disengagement
- Safety Check
- Undocking
- Authorization
- Departure Monitoring

Moderate Risks + Mitigations



Full System Risk Matrix							
			Severity				
			Negligible	Minor	Moderate	Major	Catastrophic
			1	2	3	4	5
obability + Detectability	Rare	2				R-CDH-02	
		3		R-COMM-03 R-COMM-12 R-MSN-01		R-PWR-04	
	Unlikely	4			R-AO-01 R-CDH-01 R-CDH-13 R-CDH-03 R-CDH-04 R-COMM-05 R-COMM-06 R-COMM-10 R-COMM-11 R-GNC-6 R-GNC-12 R-MOD-01 R-PROP-5 R-PROP-6 R-PROP-9 R-PWR-03 R-SRVC-05 R-SRVC-08 R-THRM-04 R-ARM-06	R-CDH-07 R-COMM-01 R-ESD-01 R-GNC-03 R-GNC-11 R-PROP-01	R-GNC-04 R-PROP-02 R-SRVC-02 R-THRM-01
		5			R-CDH-05 R-COMM-04 R-COMM-7 R-COMM-8 R-GNC-8 R-GNC-14 R-PROP-04 R-PROP-7 R-PROP-12 R-PWR-05 R-PWR-08 R-SRVC-09 R-SRVC-12 R-STRC-03 R-STRC-6 R-THRM-02 R-THRM-03 R-THRM-05 R-STRC-01	R-CDH-10 R-CDH-11 R-COMM-02 R-MSN-02 R-PROP-11 R-PWR-01 R-STRC-02 R-VAC-01 R-ARM-05	R-GNC-15 R-RAD-01



Full System Risk Matrix

			Severity				
			Negligible	Minor	Moderate	Major	Catastrophic
			1	2	3	4	5
Pr	Possible	6			R-CDH-12 R-MG-01 R-OUT-01 R-SRVC-04 R-TP-01 R-ARM-08	R-CDH-06 R-CDH-09 R-COMM-9 R-GNC-02 R-GNC-5 R-GNC-09 R-GNC-13 R-PROP-8 R-PWR-02 R-PWR-06 R-PWR-07 R-SRVC-01 R-SRVC-06 R-SRVC-07 R-SRVC-10 R-STRC-5 R-THRM-06 R-VAC-02	R-CDH-08 R-GNC-01 R-GNC-10 R-SRVC-03 R-ARM-04
		7				R-GNC-7 R-GNC-16 R-PROP-10 R-PWR-09 R-RAD-03 R-SRVC-11 R-STRC-04 R-THRM-07 R-ARM-01 R-ARM-07	R-PROP-03 R-RAD-02 R-ARM-03
	Likely	8					R-MM-01 R-MM-02
		9					
	Certain	10					

Engineering Development Risk Definition

Risk ID	Description
R-CDH-07	Delayed or failed autonomous safe mode command following detection of a fault
R-COMM-09	Failure to autonomously switch to safe-mode beacon following loss of primary transceiver chain
R-GNC-02	Autonomous rendezvous or docking algorithm failure
R-GNC-09	Relative navigation errors exceed allowable position or attitude bounds during proximity operations
R-GNC-07	Autonomous approach or retreat fails under nominal latency or sensor degradation
R-GNC-16	COTS GNC components lack sufficient qualification or heritage for autonomous long-duration operations
R-PROP-10	COTS propulsion components lack sufficient qualification for long-duration space operations

Engineering Development Risk Definition

Risk	Descriptions
R-PWE-09	COTS power components lack sufficient qualification for long-duration space operations
R-RAD-03	Radiation-induced degradation of thermal coatings, MLI, or heaters reduces thermal control effectiveness
R-SVC-11	Verification of module transfer fails to detect unsuccessful handoff
R-STRC-04	Long-term material degradation from thermal cycling reduces structural strength

Engineering Development - Risk Mitigation

Risk ID	Mitigations
R-CDH-07	- Independent safe mode controller - watchdog, reset protection
R-COMM-09	
R-SRVC-02	Implement independent retreat logic with predefined escape trajectories triggered by navigation uncertainty or sensor faults, and validate extensively through Monte Carlo and hardware-in-the-loop proximity simulations.
R-GNC-09	
R-GNC-07	
R-GNC-16	Select spaceflight-qualified or radiation-tested components where possible and perform environmental qualification testing to mission life margins before integration.
R-PROP-10	Require component-level hot-fire, life-cycle, and thermal vacuum testing to demonstrate long-duration reliability, and incorporate redundancy in valves or critical flow paths.

Engineering Development Risk Mitigation

Risk	Mitigation
R-PWE-09	Use space-rated converters and battery electronics when feasible, and perform derating analysis plus radiation and thermal cycling tests to validate lifetime performance.
R-RAD-03	Select radiation-resistant coatings and MLI materials with flight heritage, and validate performance using total ionizing dose testing against predicted mission dose.
R-SVC-11	Incorporate redundant confirmation sensors (load cells, limit switches, vision verification) and require positive verification before arm release or departure maneuvers.
R-STRC-04	Use materials with demonstrated resistance to thermal cycling and UV exposure, and perform accelerated life testing to validate structural margins over mission duration.

Full Mass Budgets

System Design - Mass Budget (Robotics)

Subsystem	Component	Mass (kg)
Robotics	Robotic Arm	120.00
	Rail System	
	Propellant Docking Interface	12.00
	Payload Modules	
	Subtotal	132.00

System Design - Mass Budget (Structures)

Subsystem	Component	Mass (kg)
Structures	Honeycomb Side Panels (6x)	291.02
	Honeycomb Top Plate	102.05
	Honeycomb Midplate	119.92
	Honeycomb Bottom Plate	137.96
	Corner Beam (6x)	43.53
	Brackets	138.90
	Fasteners	34.72
	Starship PAF (Payload Attach Fitting)	185.00
	Subtotal	xxx

System Design - Mass Budget (ADCS)

Subsystem	Component	Mass (kg)
ADCS	Control Moment Gyroscopes	50.00
	RCS Thrusters	175.00
	Star Tracker	1.70
	IMU	
	Subtotal	xxx

System Design - Mass Budget (Propulsion 1/4)

Subsystem	Component	Mass (kg)
Propulsion	RCS Thruster Fuel	2000.00
	Prop Tank + Bracket (Qty. 7)	12095.10
	Propellant (CHEM-Hydrazine)	15000.00
	Propellant (EP-Iodine)	2700.00
	Pressurant (Helium)	400.00
	Fuel Lines	9.00
	Helium COPV tanks (4500 psi)	48.00
	He Regulator (HP -> LP)	6.00
	Check Valve	1.00
	PRV/ Burst Disk	0.60
	He Tubing & Fittings	10.00

System Design - Mass Budget (Propulsion 2/4)

Subsystem	Component	Mass (kg)
Propulsion	He Pressure Sensor	0.40
	He Temperature Sensor	0.20
	Hydrazine Tanks	
	Hydrazine Tank Heaters	1.40
	Tank Pressure sensor	1.40
	Tank Temperature Sensor	1.40
	Tank Isolation Valve	4.90
	Cross-feed Ring (Manifold)	12.00
	manifold pressure sensor	0.20
	manifold temperature sensor	0.10
	EP Harmness (HV Cables)	10.00

System Design - Mass Budget (Propulsion 3/4)

Subsystem	Component	Mass (kg)
Propulsion	commercial service manifold	5.00
	Branch Isolation Valve	4.20
	Filter	3.00
	Flow Meter	1.80
	Pressure Sensor	0.60
	Temp Sensor	0.30
	Primary Valve (latch)	3.60
	Secondary Valve (Rafti type)	7.20
	refueling Interface	
	Vent/Purge Valve	3.00
	Thruster Gimbals	10.00

System Design - Mass Budget (Propulsion 4/4)

Subsystem	Component	Mass (kg)
Propulsion	Vent Line & Fitting	5.00
	Iodine Tank	88.00
	Iodine tank heaters	0.80
	Iodine Pressure Sensor	0.40
	Iodine Temperature Sensor	0.20
	Check Valve (iodine feed)	0.60
	Vaporizer Unit (heater)	10.00
	Hall Thruster (iodine)	50.00
	PPU	25.30
	Iodine Flow Control	2.00
	Subtotal	

System Design - Mass Budget (Power)

Subsystem	Component	Mass (kg)
Power	Batteries	60.00
	Solar Panels (Qty. 6)	300.00
	Subtotal	xxx

System Design - Mass Budget (Thermal)

Subsystem	**Component**	**Mass (kg)**
Thermal	MLI	
	Radiators	
	Subtotal	xxx

System Design - Mass Budget (Communications 1/2)

Subsystem	Component	Mass (kg)
Communications	S-Band Trancievers	5.00
	S-Band Power AMps	3.00
	X-Band HIgh Rate Transmitter	3.00
	X-Band High Power Amps	3.50
	Omni Antennas	1.20
	High Gain Antenna (Body Fixed)	3.00
	High Gain Antenna (Gimbal)	8.00
	RF Switch Matrix	2.00
	LNAs	1.00
	Diplexers	1.00

System Design - Mass Budget (Communications 2/2)

Subsystem	**Component**	**Mass (kg)**
Communications	Cryptoengine	1.50
	Cross-linked radio	5.00
	Patch antennas	0.80
	Flight Computer	4.00
	Spacewire Router	1.50
	High Altitude GNNs receiver	1.50
	Solid state recorder	3.00
	Subtotal	xxx

Full Power Budgets

System Design - Power Budget (Propulsion Peak Functionality 1/2)

Subsystem	Component	Quantity	Power (W)
Propulsion	He Regulator (HP -> LP)	2	10
	Hydrazine Tank Heaters	7	210
	Tank Isolation Valve	7	70
	Branch Isolation Valve	6	60
	Flow Meter	6	12
	Pressure Sensor	20	20
	Temp Sensor	20	20
	Primary Valve	6	60
	Secondary Valve	6	60

System Design - Power Budget (Propulsion Peak Functionality 2/2)

Subsystem	Component	Quantity	Power (W)
Propulsion	Vent/Purge Valve	6	60
	Iodine tank heaters	4	480
	Vaporizer Unit (heater)	2	600
	Hall Thruster (iodine)	2	12000
	PPU	2	800
	Iodine Flow Control	2	20
	Thruster Gimbals	2	80
	EP Harness (HV cables)	1	50
	Peak Total: 14612.00	Minimum: 16365.44	Target: 21275.07

System Design - Power Budget (Propulsion Safe Mode)

Subsystem	Component	Quantity	Power (W)
Propulsion	Hydrazine Tank Heaters	7	70
	Flow Meter	6	3
	Pressure Sensor	20	5
	Temp Sensor	20	5
	Iodine tank heaters	4	120
	Vaporizer Unit (heater)	2	100
	PPU	2	50
	Iodine Flow Control	2	5
	Peak Total: 358	Minimum: 400.96	Target: 521.25

System Design - Power Budget (Propulsion Nominal Functions 1/2)

Subsystem	Component	Quantity	Power (W)
Propulsion	He Regulator (HP -> LP)	2	5
	Hydrazine Tank Heaters	7	175
	Flow Meter	6	6
	Pressure Sensor	20	10
	Temp Sensor	20	10
	Iodine tank heaters	4	320
	Vaporizer Unit (heater)	2	400
	Hall Thruster (iodine)	2	6000
	PPU	2	600

System Design - Power Budget (Propulsion Nominal Functions 2/2)

Subsystem	Component	Quantity	Power (W)
Propulsion	Iodine Flow Control	2	10
	Thruster Gimbals	2	20
	EP Harness (HV cables)	1	30
	Peak Total: 7586	Minimum: 8496.32	Target: 11045.22

System Design - Power Budget (Communications Peak Functionality 1/2)

Subsystem	Component	Quantity	Power (W)
Communications	S-Band Trancievers	2	20
	S-Band Power Amp	2	44
	X-Band high rate transmitter	1	15
	X-Band high power amp	1	50
	Omni antennas	4	0
	High gain antenna (body fixed)	1	0
	High gain antenna (gimbal)	1	5
	RF switch matrix	1	5
	LNAs	2	3

System Design - Power Budget (Communications Peak Functionality 2/2)

Subsystem	Component	Quantity	Power (W)
Communications	Diplexers	-	0
	Cryptoengine	1	8
	Cross-linked radio	2	24
	Patch Antenna	-	0
	Flight computer	1	25
	solid state recorder	1	12
	high alt GNNs receiver	1	10
	Spacewire router	1	6
	Peak Total: 227.00	Minimum: 254.24	Target: 330.512

System Design - Communications Budget (Propulsion Safe Mode)

Subsystem	Component	Quantity	Power (W)
Communications	S-Band Transceivers	1	10
	S-Band Power Amp	1	22
	Omni antennas	4	0
	RF switch matrix	1	5
	LNAs	2	3
	Diplexers	-	0
	Cryptoengine	1	8
	Flight computer	1	15
	Peak Total: 63	Minimum: 70.56	Target: 91.728

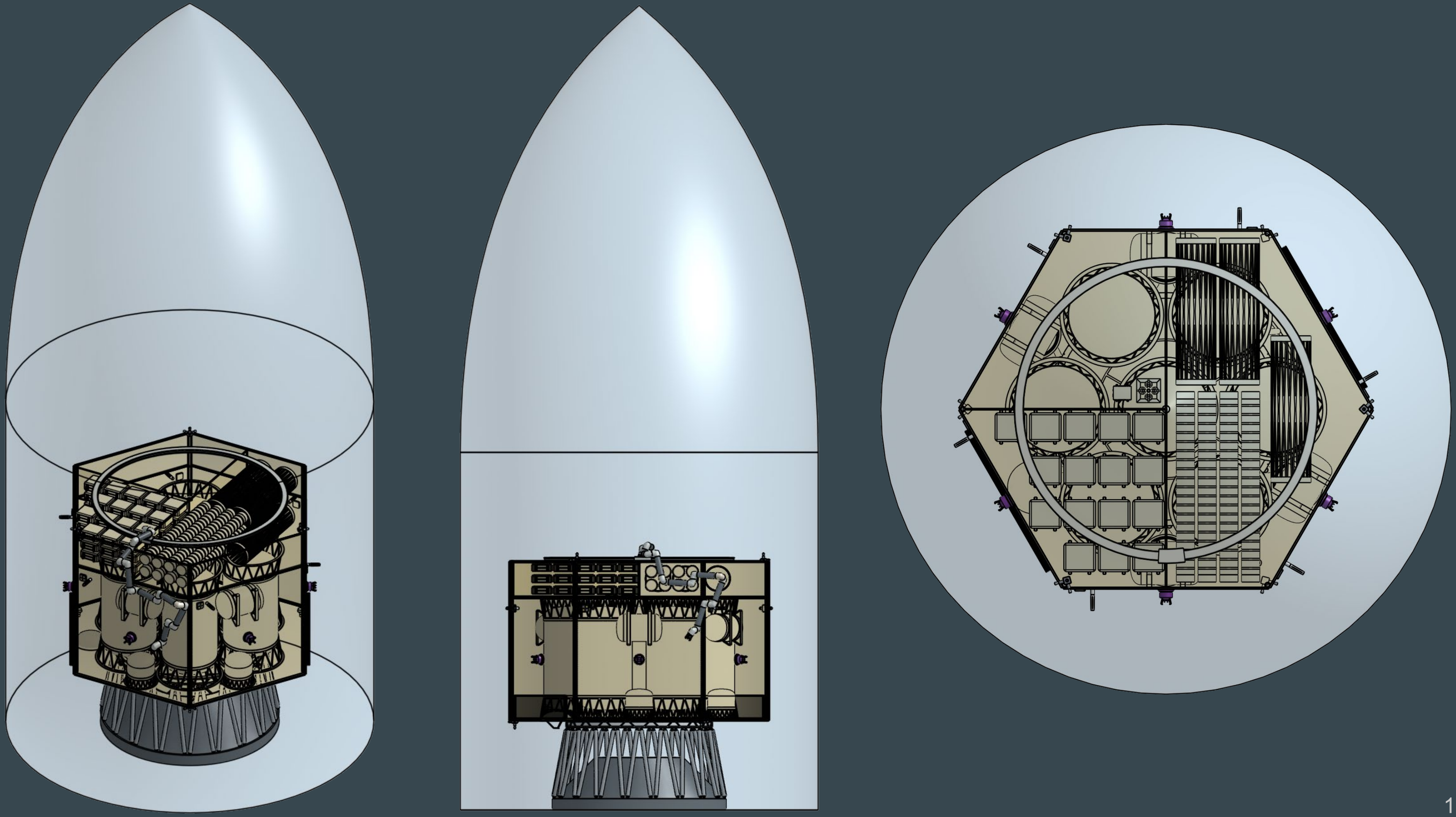
System Design - Power Budget (Communications Nominal Functions 1/2)

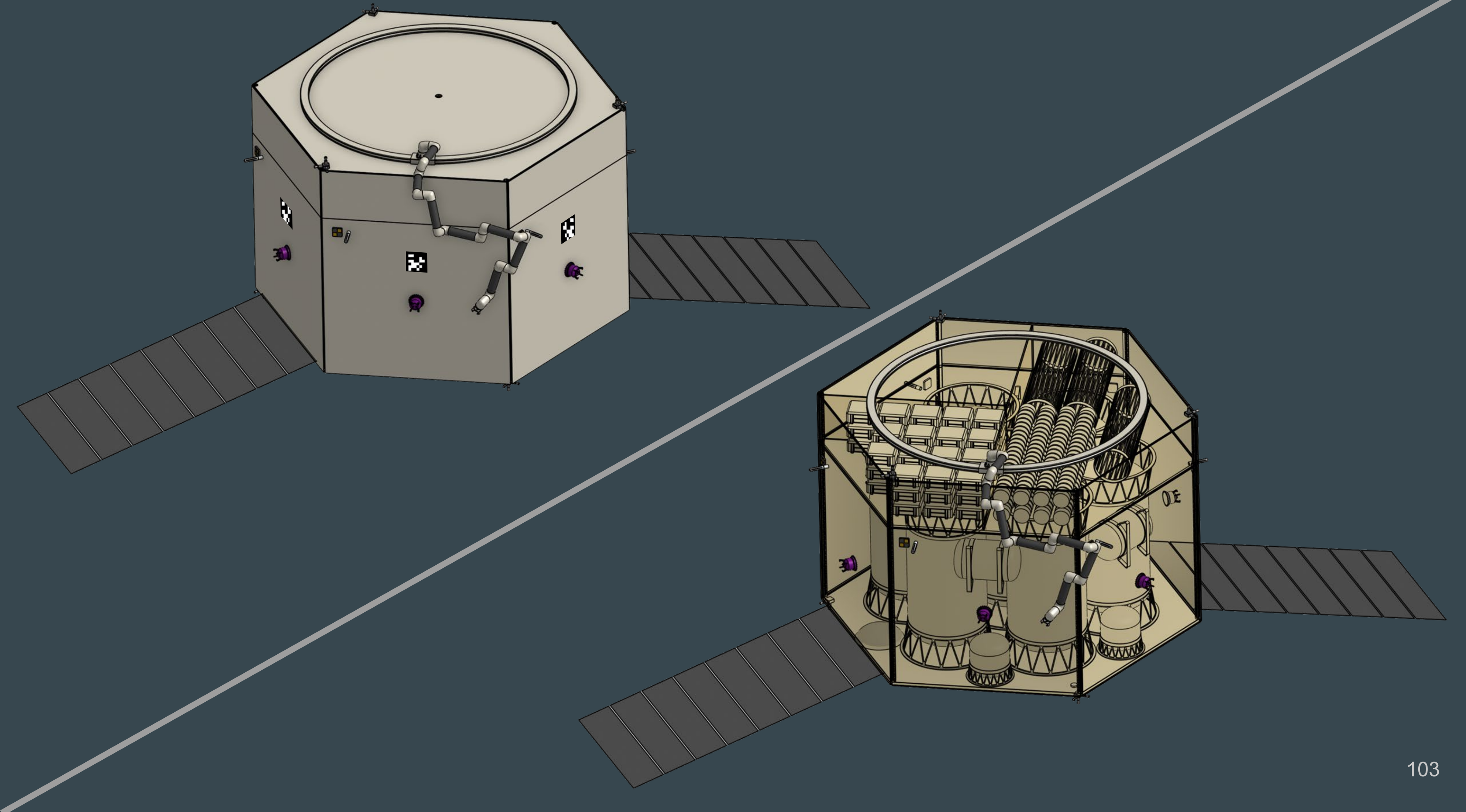
Subsystem	Component	Quantity	Power (W)
Communications	S-Band Transceivers	2	20
	S-Band Power Amp	2	44
	Omni antennas	4	0
	RF switch matrix	1	5
	LNAs	2	3
	Diplexers	-	0
	Cryptoengine	1	8
	Cross-linked radio	2	24
	Patch Antenna	-	0

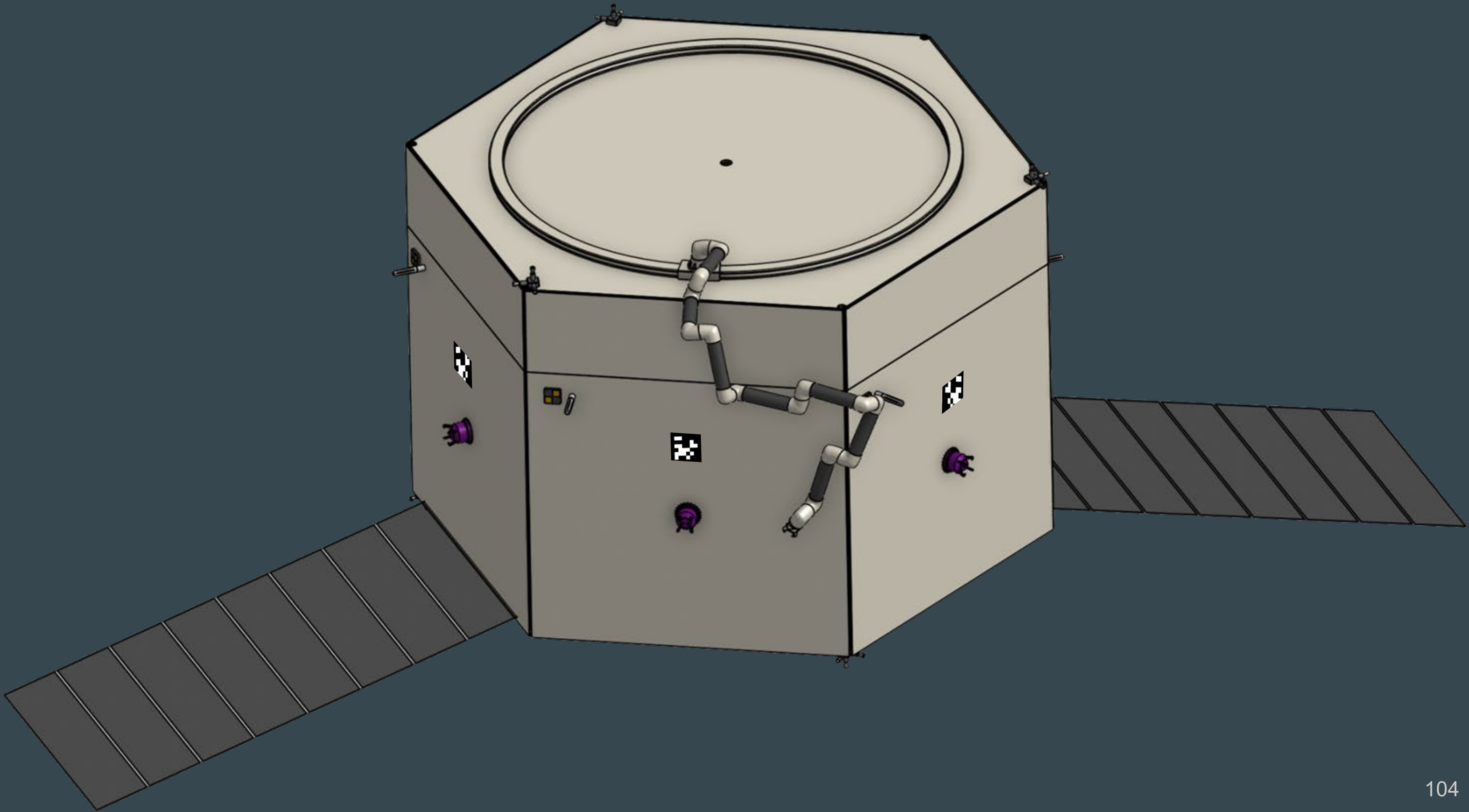
System Design-Power Budget (Communications Nominal Functions 2/2)

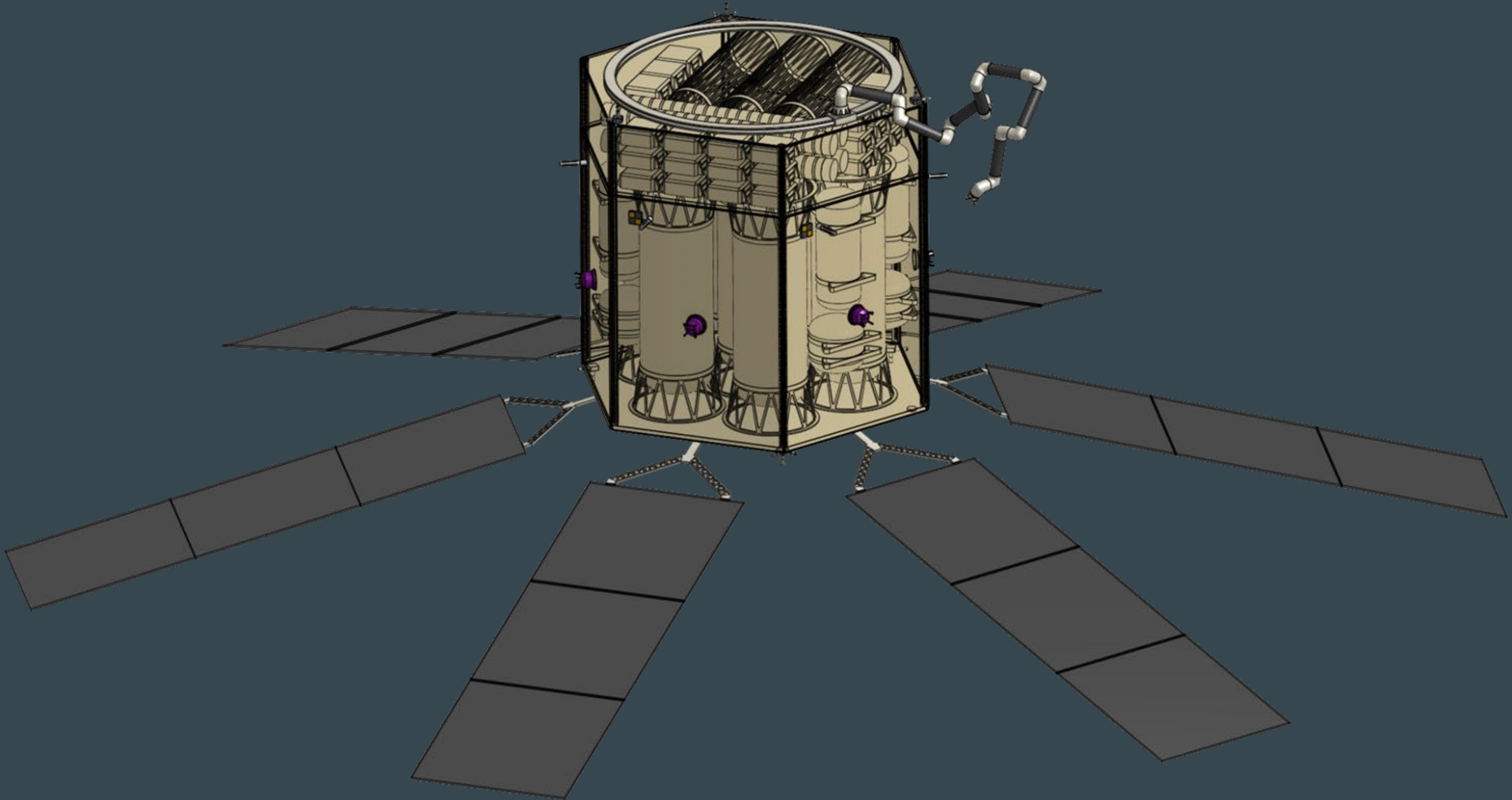
Subsystem	Component	Quantity	Power (W)
Propulsion	Flight computer	1	25
	solid state recorder	1	12
	high alt GNNs receiver	1	10
	Spacewire router	1	6
	Peak Total: 157	Minimum: 175.84	Target: 228.60

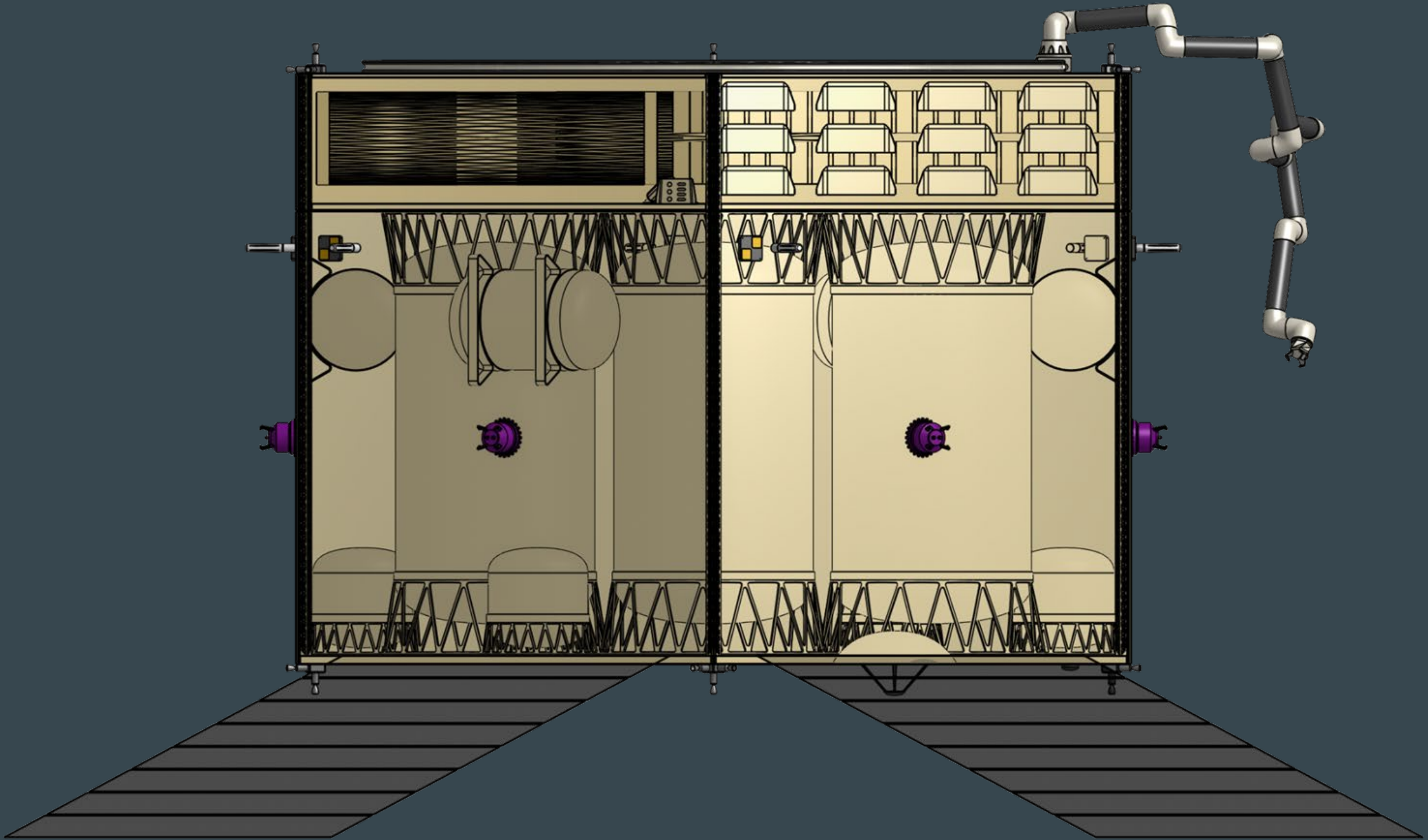
CAD MODEL

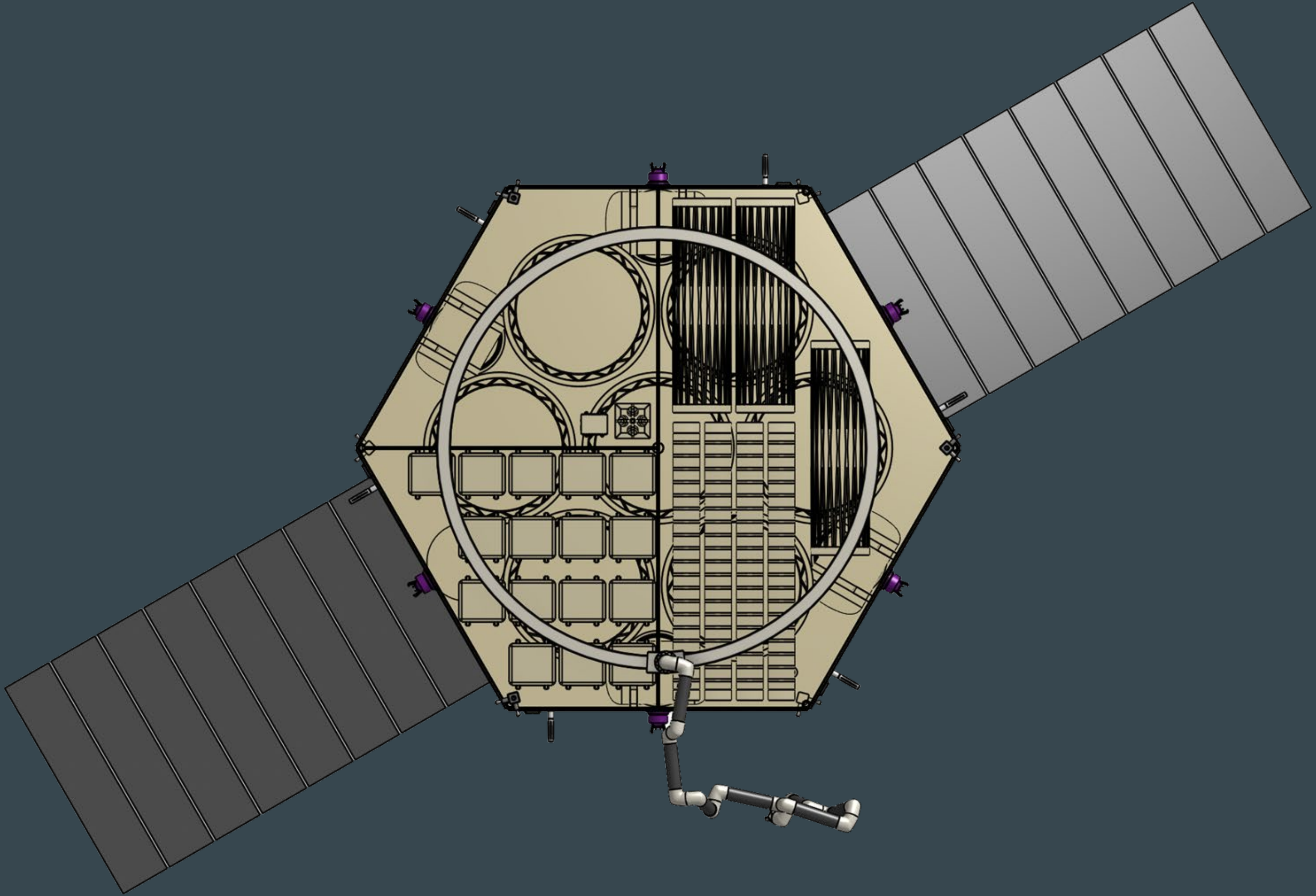


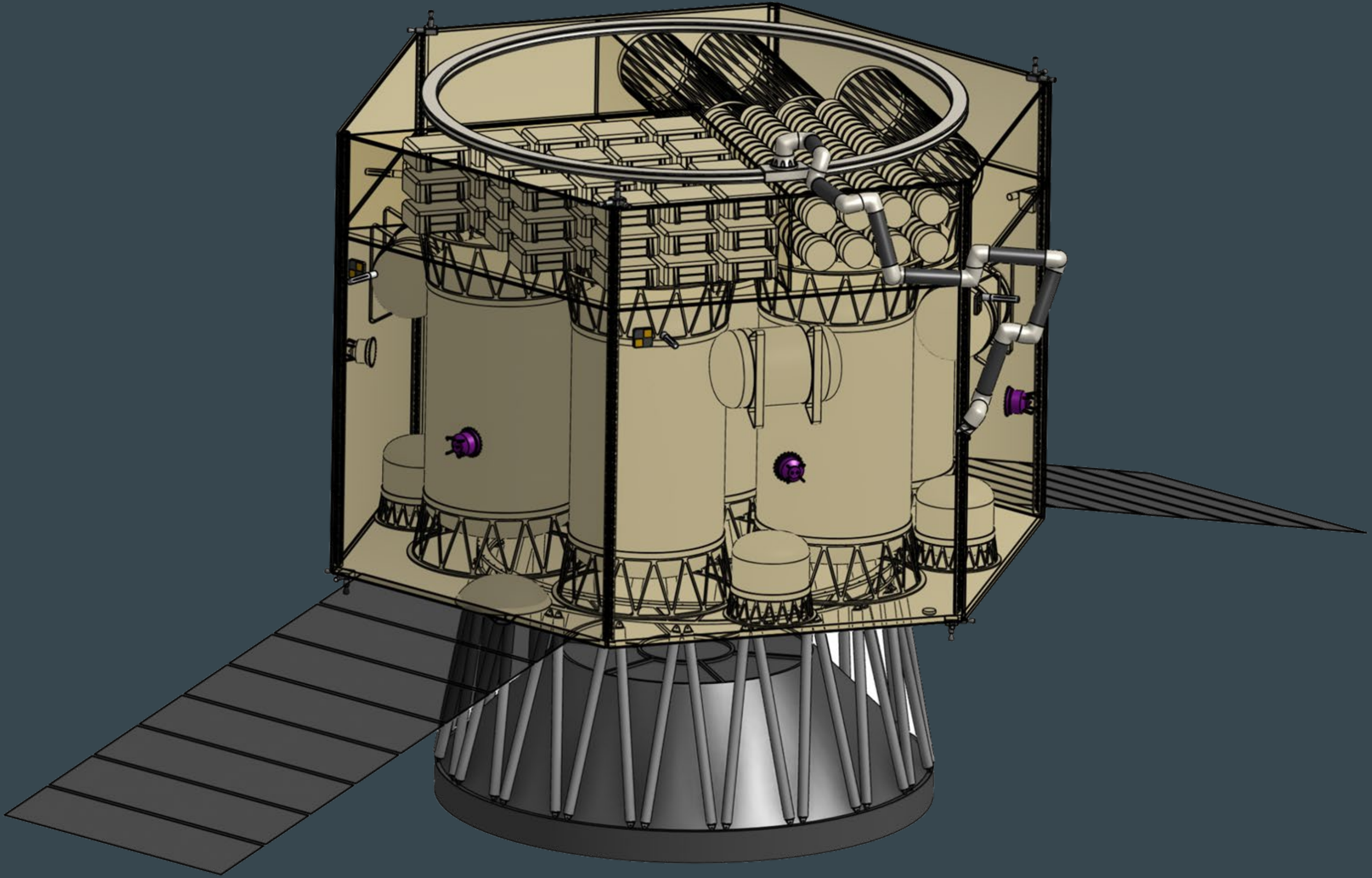


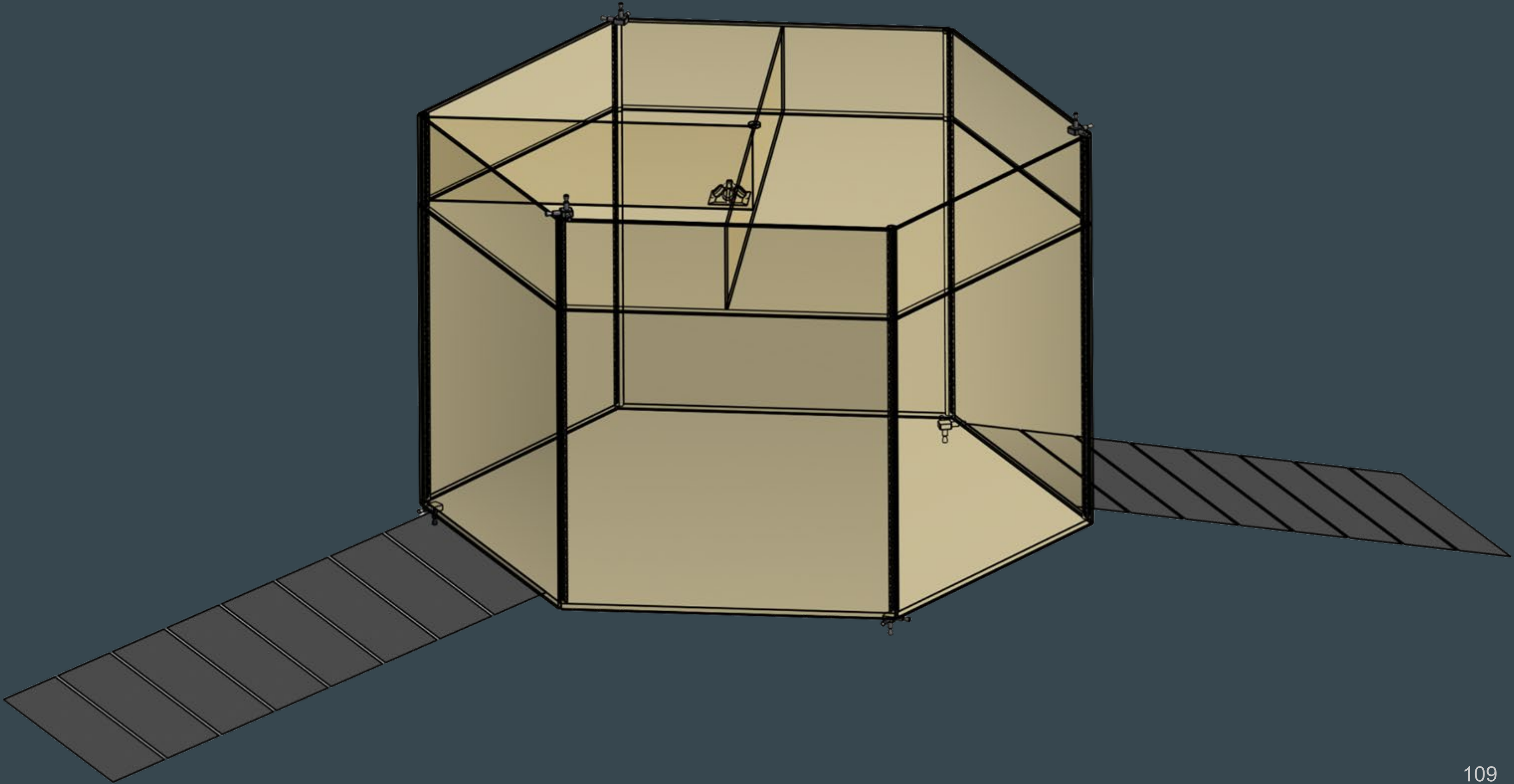


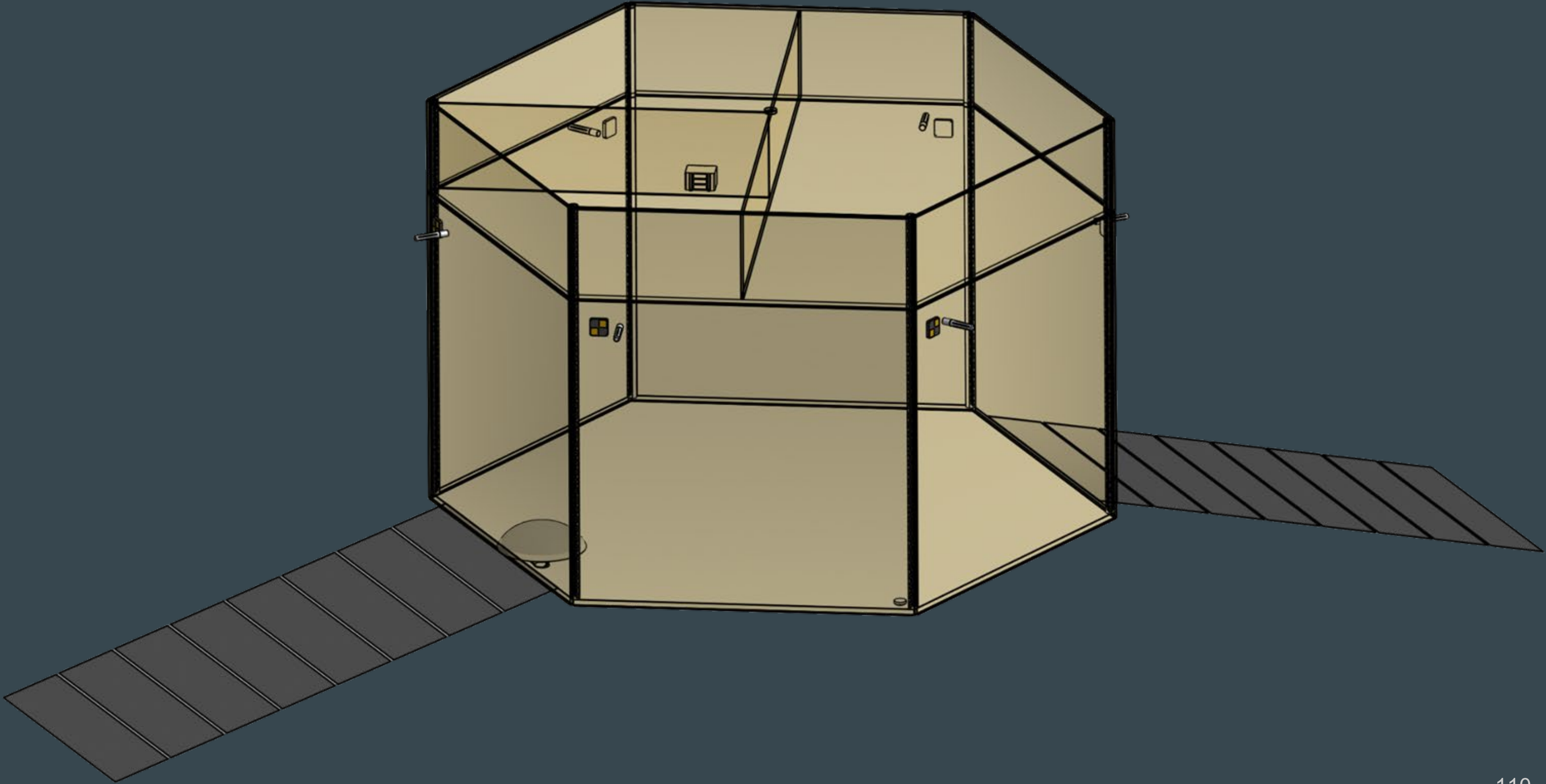


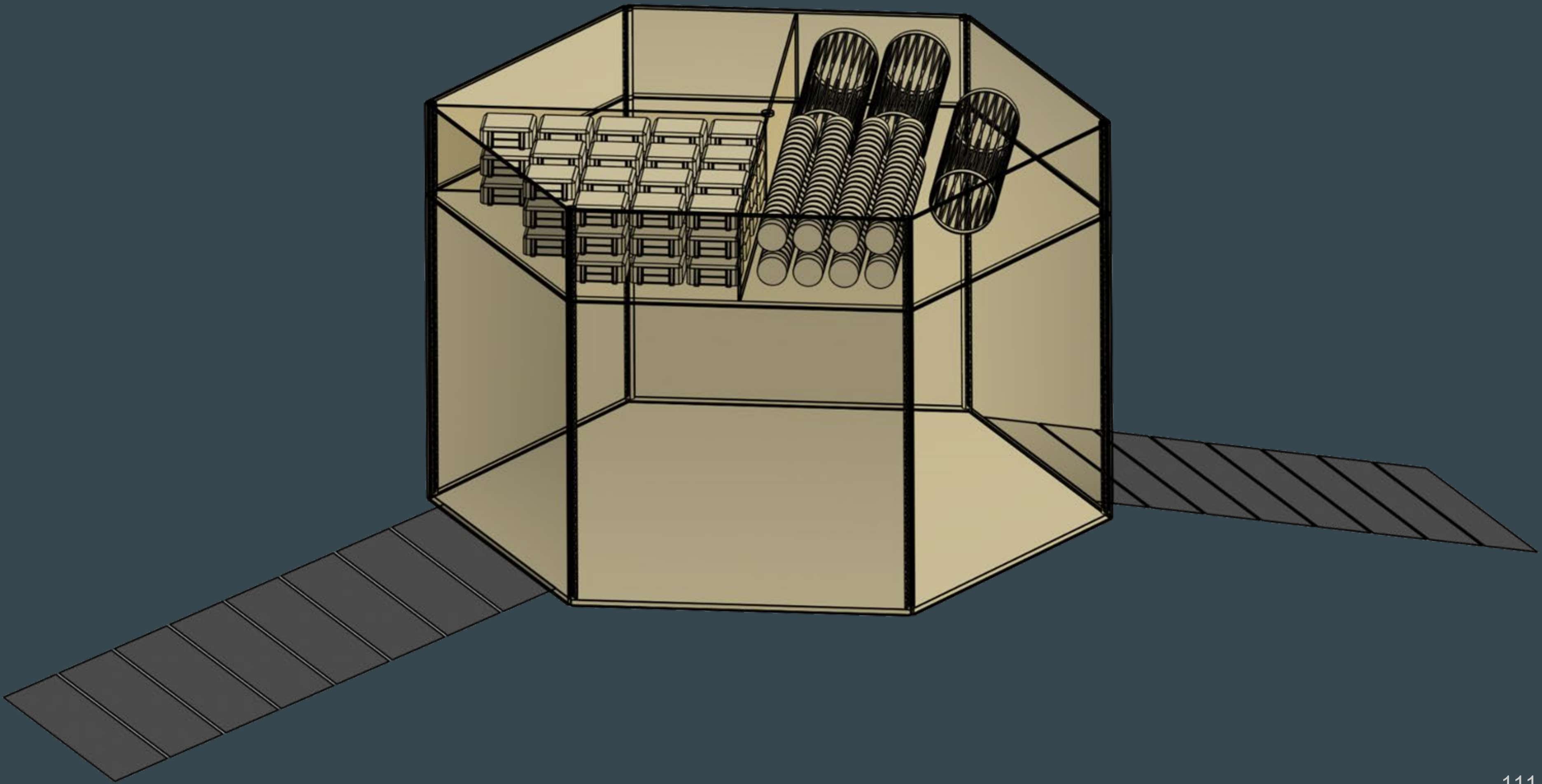


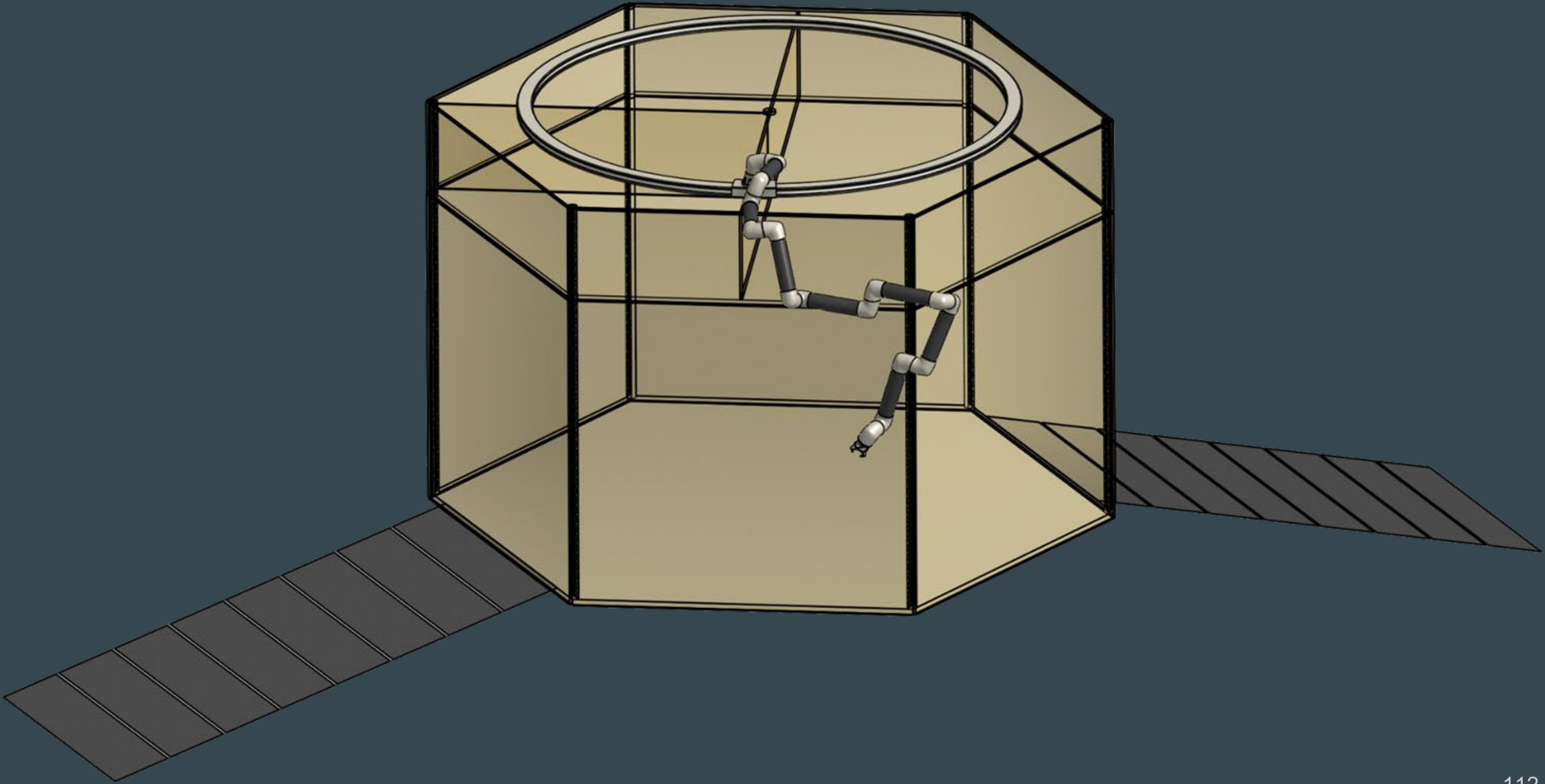


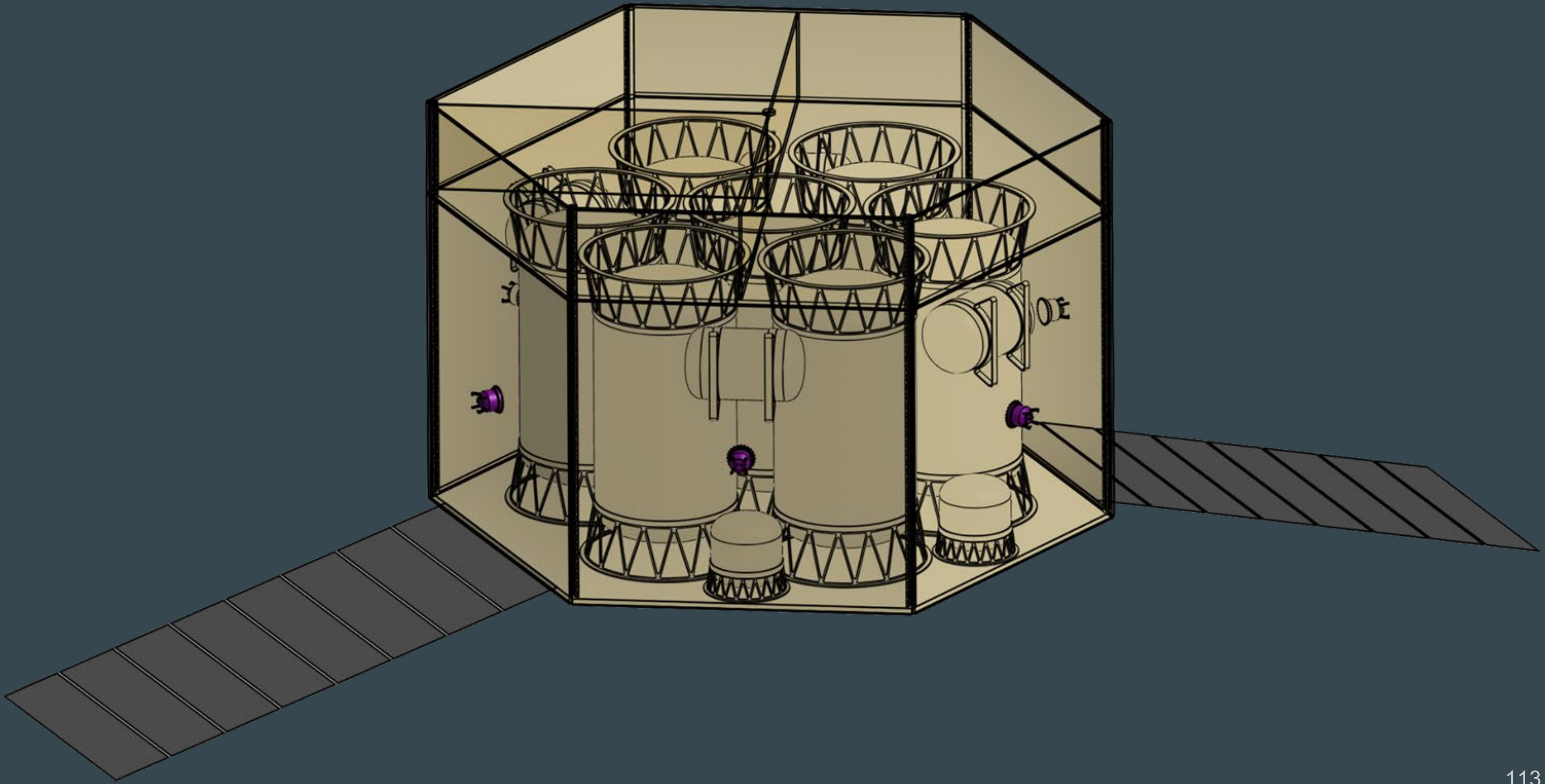


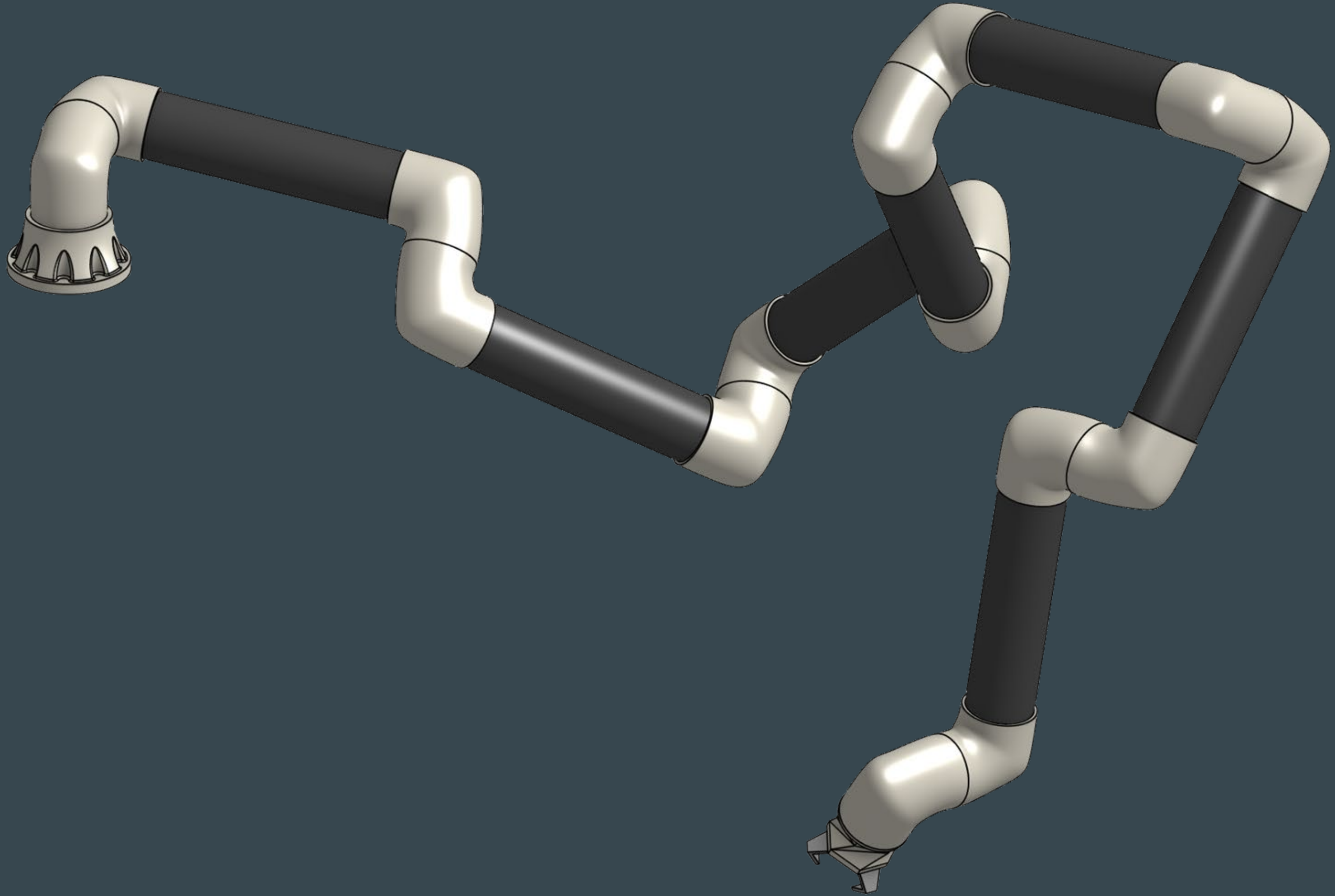


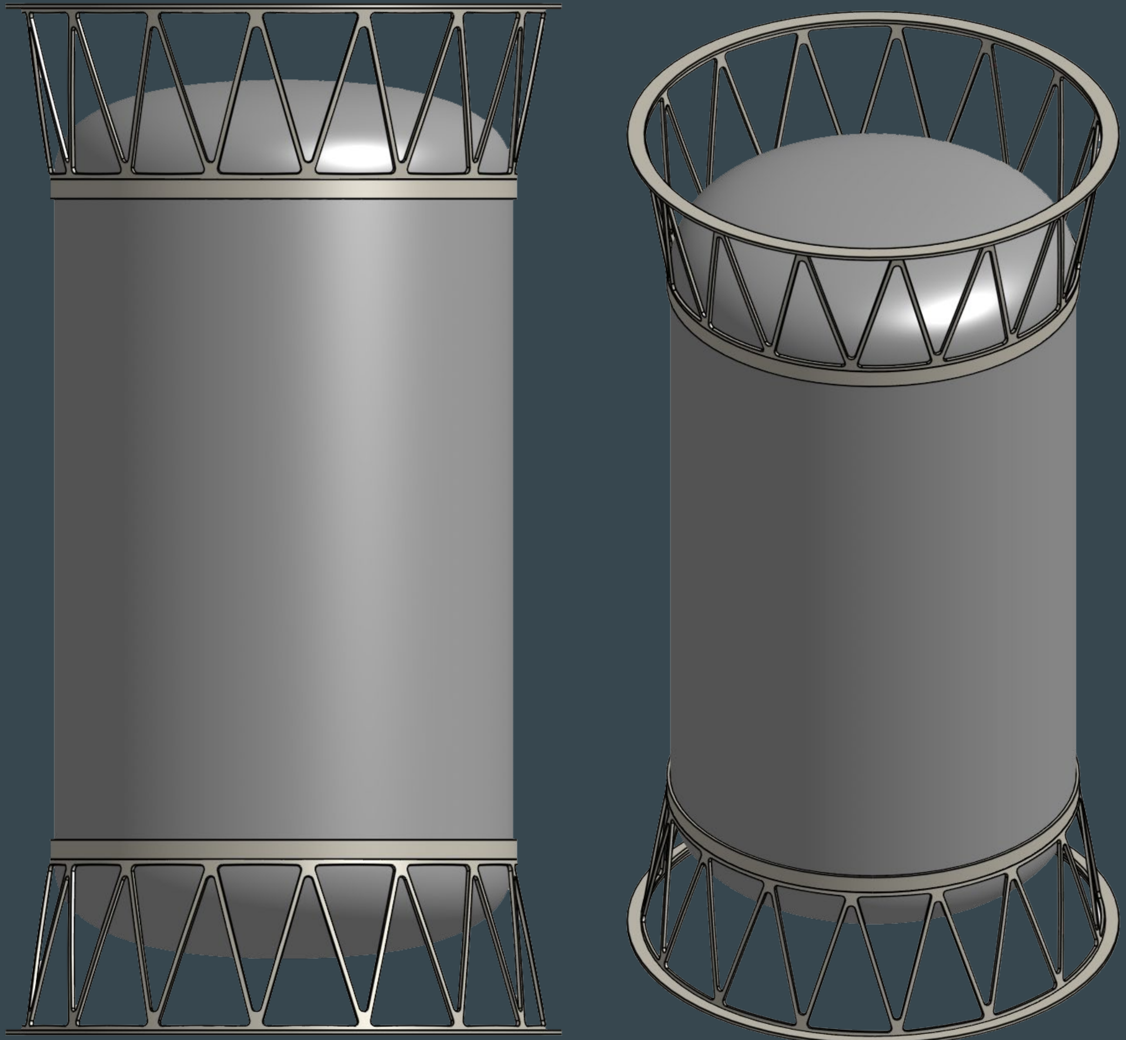


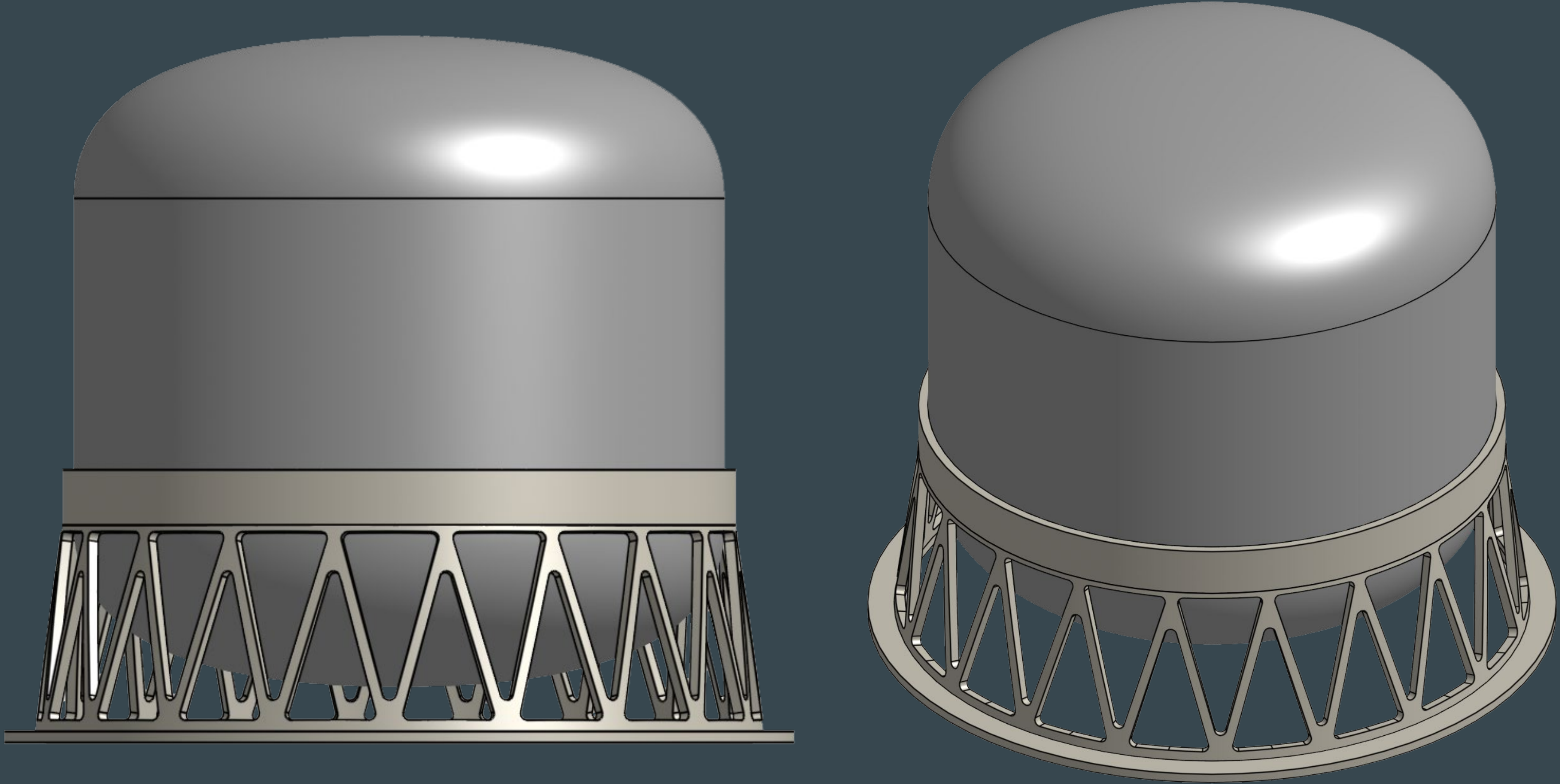


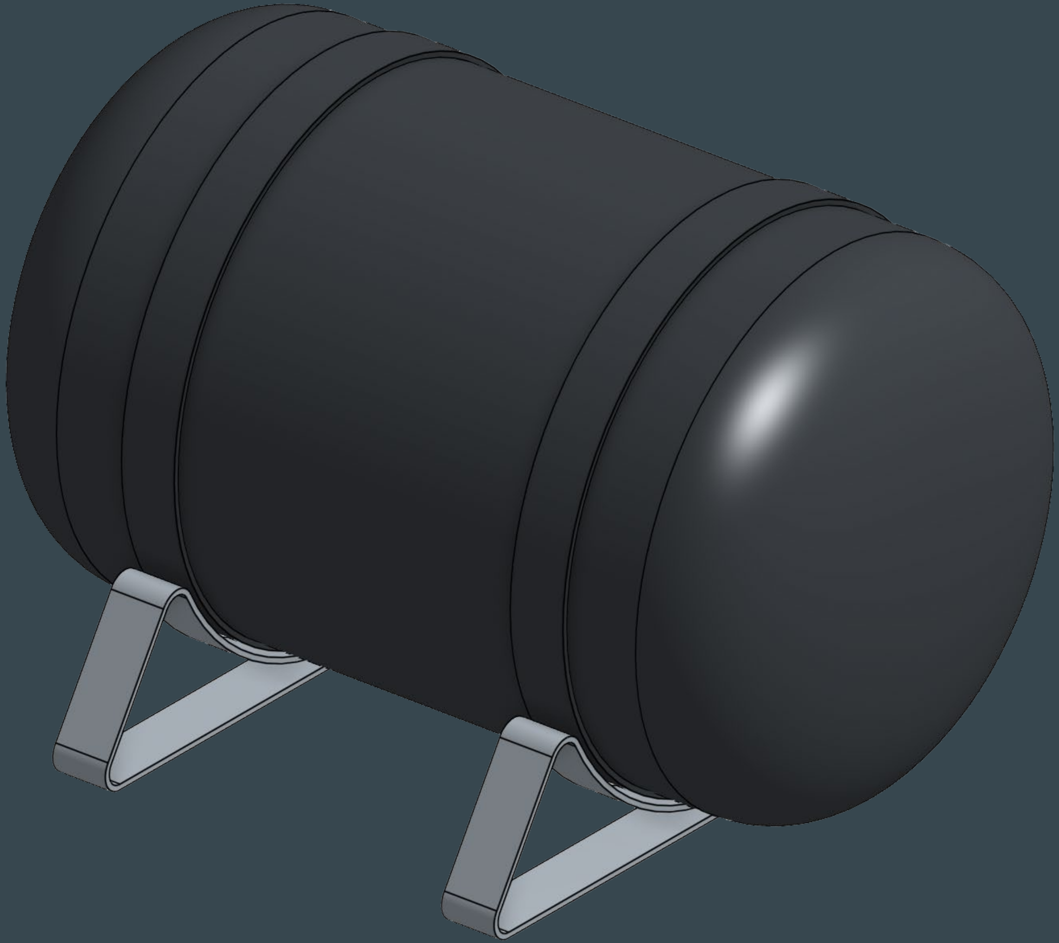


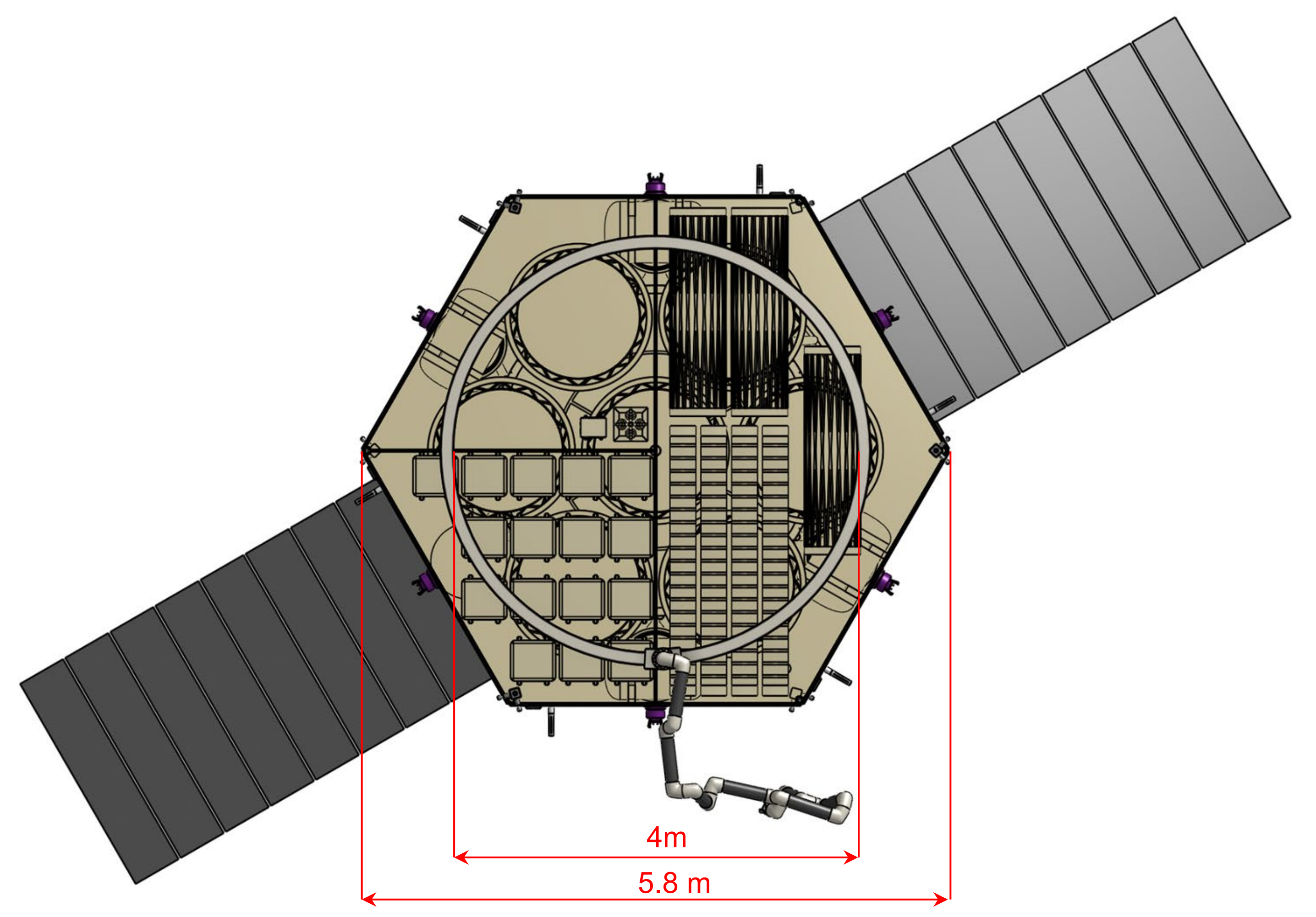











4m
5.8 m

Top-Level Mission Requirements

The spacecraft must follow the following requirements outlined by the project description

- The spacecraft shall allow for modifications to baseline configurations.
- The spacecraft shall be reusable for multiple client satellites.
- The spacecraft shall be capable of completing servicing operations in orbit without reliance on human involvement.
- The spacecraft shall be capable of transferring liquid propellant to a client satellite.
- The spacecraft shall be capable of transferring replacement components to a client spacecraft.
- The spacecraft shall utilize technologies which would be feasible within 5 years of development.

Top-Level Mission Requirements

The spacecraft must follow the following requirements, determined by trade studies and research

- The spacecraft shall be capable of obtaining required replacement components for servicing clients from depot spacecraft that hold replacement components.
- The spacecraft shall be capable of refueling itself from depot spacecraft that contain fuel.
- The spacecraft shall meet the payload requirements of Starship (SpaceX).
- The spacecraft shall be capable of transmitting data while in orbit.
- The spacecraft shall be capable of reaching and operating in a high MEO orbit (21,000 km), including consideration for all environmental factors.
- The spacecraft shall be capable of operating MEO and GEO servicer client satellites
- The spacecraft shall do no harm to any client spacecraft.
- The spacecraft shall have the capability to house components for client satelite upgrades/repairs.