



FACILITATING LUNAR OPERATIONS: THE LASER SINTERING ROBOTIC HEXAPOD MISSION

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MEET THE AULUNA TEAM



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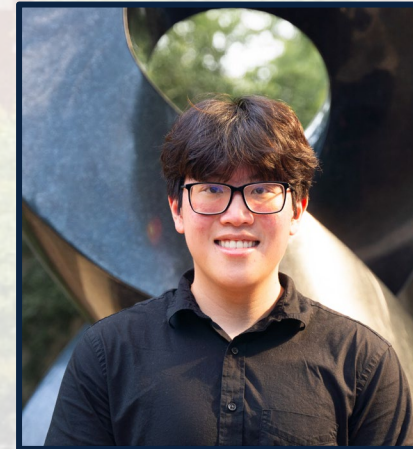
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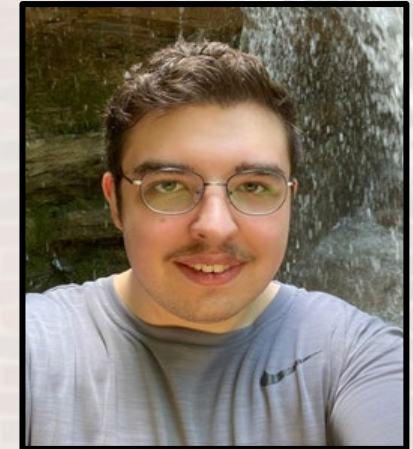
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MISSION AND PROJECT OVERVIEW

THE LASER SINTERING ROBOTIC HEXAPOD MISSION

AN OVERVIEW

■ Problem:

- Dust plume generation
- Stability upon landing is needed for consistent lunar operations
- Extreme terrain conditions in future lunar and Martian missions

■ Solution:

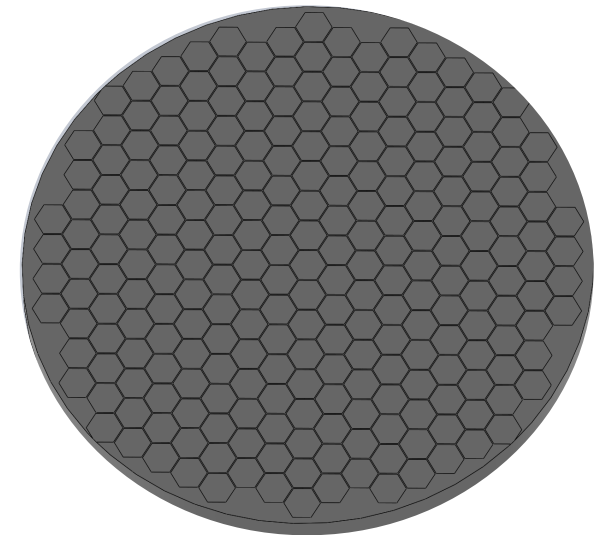
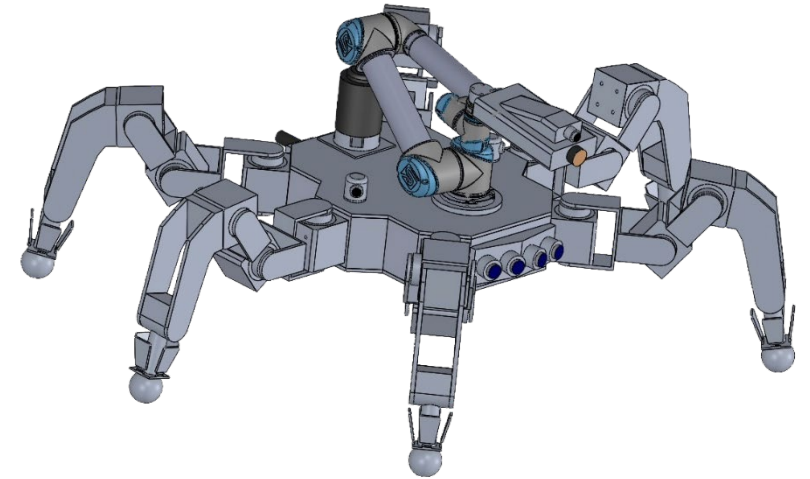
- Build dust mitigating landing pads to reduce plume size and provide stable launch and landing sites
- Prove the utility of a hexapod mobility system for future use

■ How it Solves the Problem:

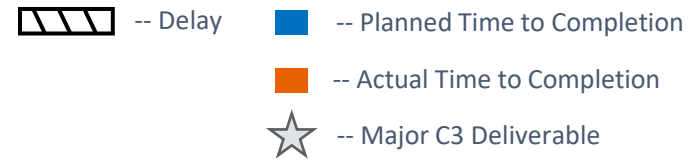
- The autonomous rover will utilize lunar regolith to laser sinter launch and landing pads (LLPs) while being able to navigate the harsh lunar surface with a novel hexapod mobility system

■ Current Project State:

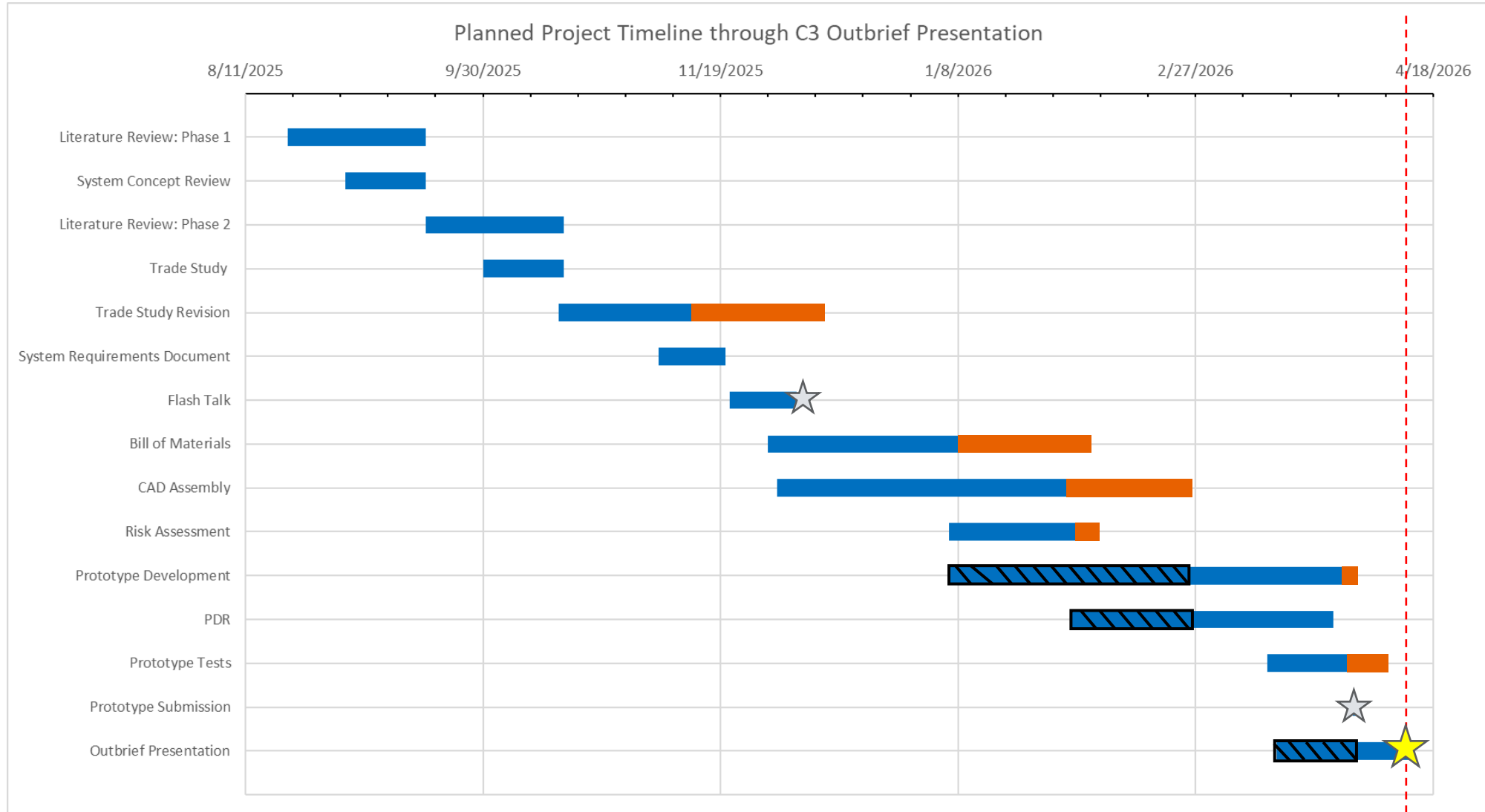
- Conceptual design complete



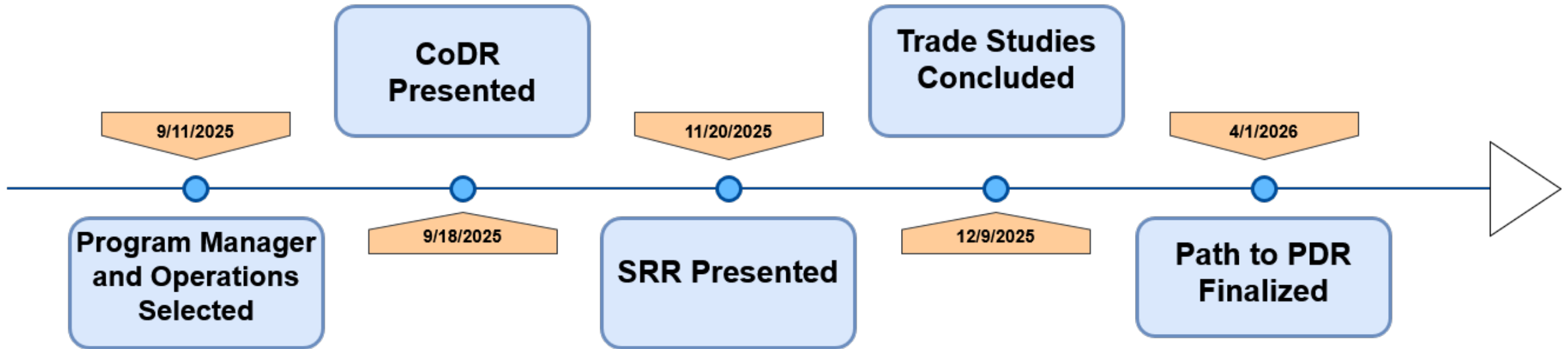
2.4 PROJECT TIMELINE



Today



2.4 PROJECT TIMELINE: KEY DATES





OUR OBJECTIVES ARE DESIGNED TO FACILITATE CURRENT AND FUTURE LUNAR OPERATIONS

Mission Goals

- Support NASA's Moon to Mars Architecture
- NASA's Lunar Surface Innovation Initiative under the Space Technology Mission Directorate (fostering "extreme access")

Mission Objectives

- Construct one 18-meter LLP for future spacecraft use
- Demonstrate the feasibility and utility of a hexapod mobility system in the lunar environment

Operational Objectives/Drivers

- R&D Period
- Launch/Transport
- Surviving the Lunar Night
- Controls Engineering
- Autonomous Systems

Success Criteria

- Construction of 18-meter LLP (primary) or 10-meter LLP (secondary)
- Completion of mobility assessment tasks
- Survival of lunar night

Design Drivers

- Lunar operations
- Lunar night survival (mission duration of a couple months)
- Griffin Lander as the delivery vehicle
- High amount of continuous power required

1.1 TECHNICAL IMPACT OVERVIEW

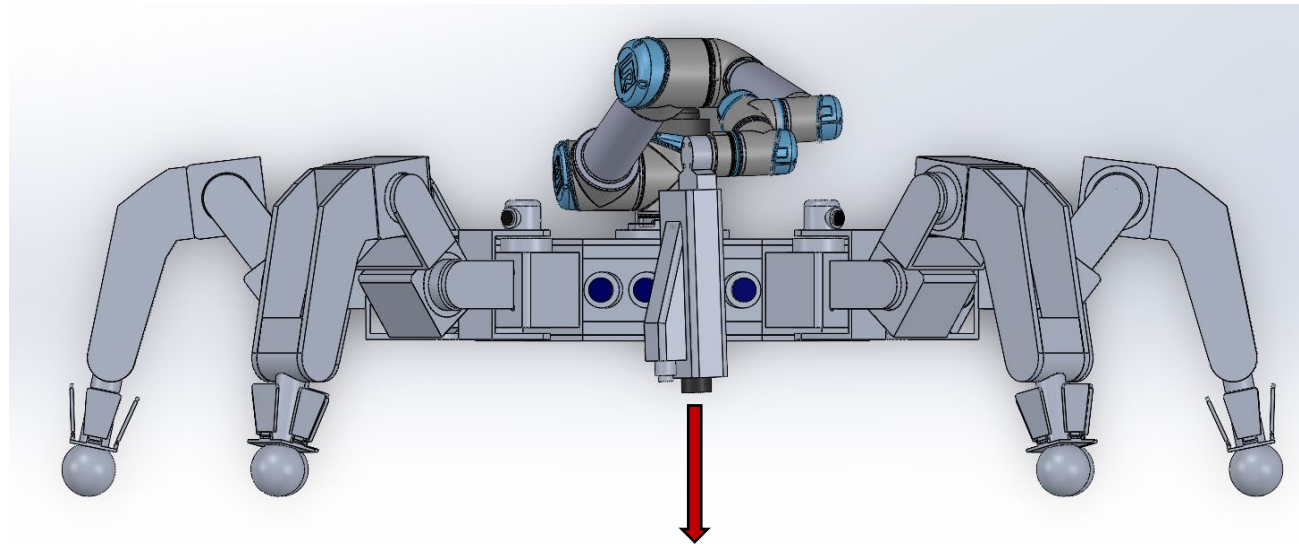
1. The LSRH mission would advance lunar operations by increasing the reliability of lunar operations
2. Achieving the LSRH's mission goals will allow for the stable transport and export of materials, personnel, and would directly enable the Artemis program's lunar permanence efforts
3. Hexapod mobility must be developed to full TRL maturity, as well as laser-sintering as an ISRU technique



Credit: NASA

1.3 INNOVATION OVERVIEW

1. Hexapod mobility has never been demonstrated in space
2. Hexapod mobility is being proposed by academia, but no missions yet utilize it
3. Small scale experiments of laser sintering have been executed in testing on the ISS using stainless steel
4. Laser sintering is uniquely suited for utilizing regolith to produce solid, strong structures. Hexapod mobility is uniquely suited for traversing the many slopes of the lunar surface



1.4 THE 2026 NASA CIVIL SPACE SHORTFALLS

CONNECTION TO THE LSRH MISSION

SF03: Safely, routinely, and precisely land large systems on the lunar surface.

- 3.3 Perform stable touchdown and operation of large vehicles on uneven, sloped, and undulating lunar surfaces.
- 3.4 Provide surface support infrastructure to routinely land on and ascend from the lunar surface.



Credit: Blue Origin

1.4 THE 2026 NASA CIVIL SPACE SHORTFALLS

CONNECTION TO THE LSRH MISSION

SF04: Deploy, assemble, and construct complex structures on the lunar surface.

- 4.1 Perform site preparation and bulk regolith manipulation for infrastructure construction, including landing pads, berms, regolith overburden for radiation protection.
- 4.2 Deploy load-bearing structures on the lunar surface.
- 4.3 Autonomously assemble and construct structures on the lunar surface.
- 4.4 Construct structures on the lunar surface through advanced manufacturing techniques.



Credit: NASA



1. Launch from Earth



2. Land near the south pole, and deploy from the Griffin Lander



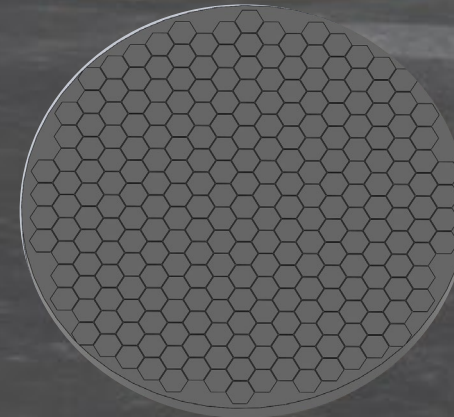
3. Maneuver to landing pad site



4. Turn on laser payload and initiate sintering process



5. Construct landing pad using individually sintered tiles



6. Enter hibernation state to survive the lunar night



7. Repeat from step 4



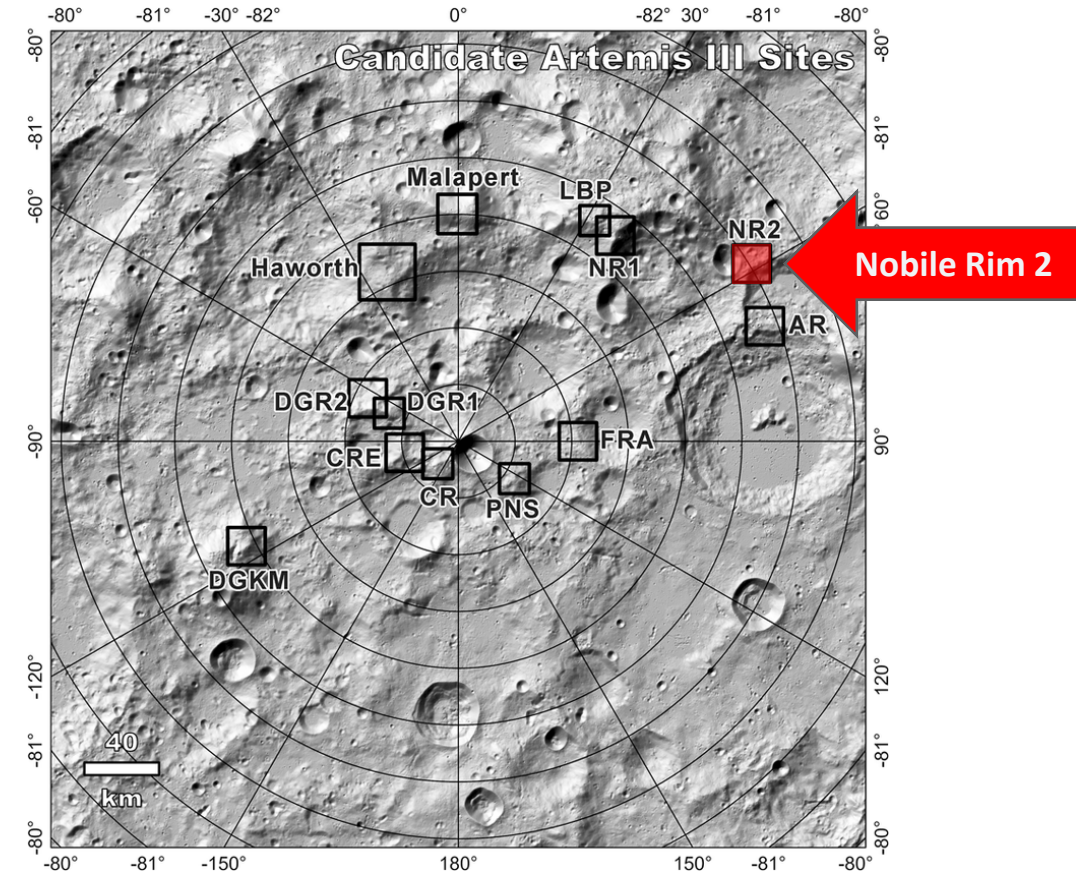
THE LSRH MISSION FOLLOWS ARTEMIS LANDING SITES

Location:

- Following Artemis candidate landing sites of the Lunar South Pole
 - Prospective landing site is **Nobile Rim 2 (NR2)** -
84°12'5.61"S and 60°41'59.61"E

Advantages of Nobile Rim 2:

- **Short night cycle** allowing for **maximum sunlight exposure**
- Best possible night cycle is estimated to last **41 hours**
- Excellent communication line of sight for astronauts and other assets



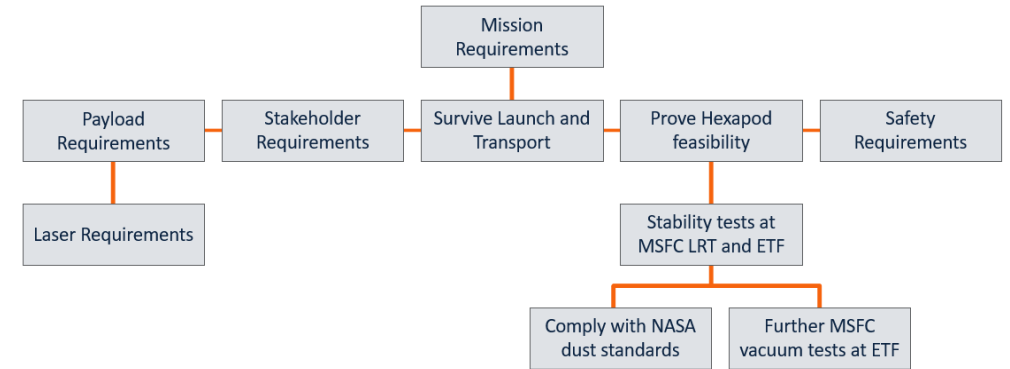


LSRH DESIGN OVERVIEW

REQUIREMENTS OVERVIEW

Functional	Performance	Constraint	Verification
R-MIS-010 (1)	R-MOB-020 (2)	R-MIS-030 (1)	R-MIS-040 (1)
R-MIS-020 (1)	R-MOB-030 (2)	R-LAD-010 (1)	R-MIS-050 (1)
R-LAD-020 (1)	R-MOB-060 (2)	R-MOB-050 (2)	R-MIS-060 (2)
R-PLD-010 (2)	R-LAS-020 (2)	R-COM-010 (2)	R-MIS-070 (1)
R-PLD-020 (2)	R-LAS-030 (2)	R-PWR-010 (2)	R-MOB-070 (2)
R-MOB-010 (2)	R-LAS-040 (2)	R-SAF-010 (1)	R-MIS-080 (1)
R-MOB-040 (2)	R-LAS-050 (2)	R-LAS-070 (2)	
R-LAS-010 (2)	R-LAS-060 (2)		
R-GNC-010 (2)	R-GNC-050 (3)		
R-GNC-020 (3)	R-THM-010 (2)		
R-GNC-030 (3)			
R-GNC-040 (3)			
R-GNC-060 (3)			
R-GNC-070 (3)			
R-SAF-020 (1)			

Verification	Verification Method
R-MIS-040 (1)	Measurement
R-MIS-050 (1)	Measurement
R-MIS-060 (2)	Measurement
R-MIS-070 (1)	Measurement
R-MOB-070 (2)	Inspection
R-MIS-080 (1)	Inspection



COM - Communication
 GNC - Guidance, Navigation, and Control
 LAD - Launch and Delivery
 LAS - Laser
 MIS - Mission
 MOB - Mobility
 PLD - Payload
 PWR - Power
 SAF - Safety
 THM - Thermal
 (#) - Tier of the Requirement

LSRH COMPONENTS

Mobility

- 6-legged hexapod, rectangular body section, spherical foot-contacts, spring-loaded regolith sink prevention mechanism

Laser Payload

- Fiber optic laser, mounted on top of body segment on a 6-DOF robot arm

Thermal

- TCS consists of heating circuits, thermal coating, and radiators

Power System

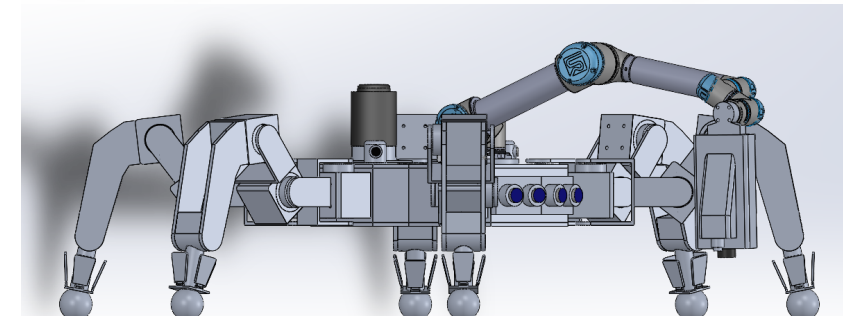
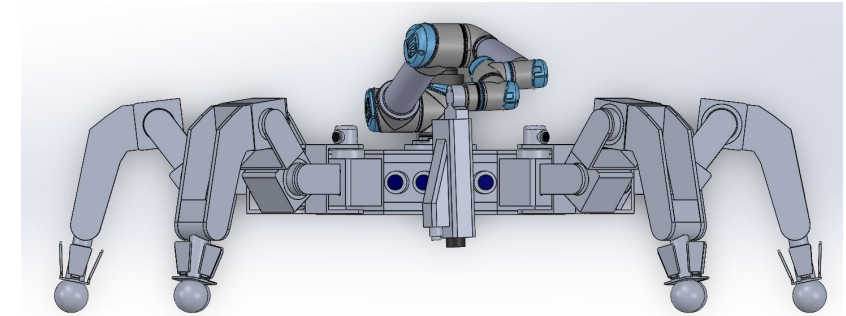
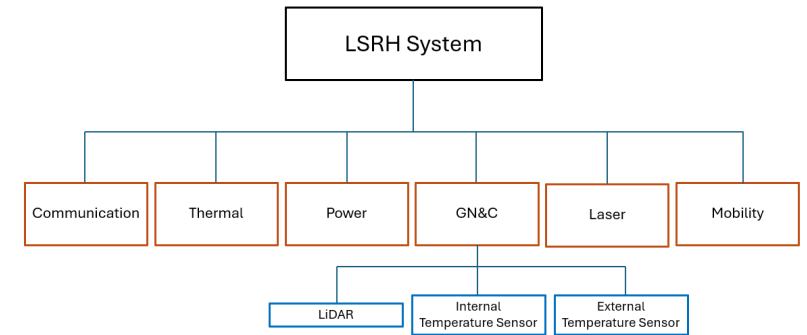
- Tethered connection to Astrobotic Griffin Lander with boom

Communication

- Antennas send/receive to Griffin Lander, for uplink and downlink to mission control

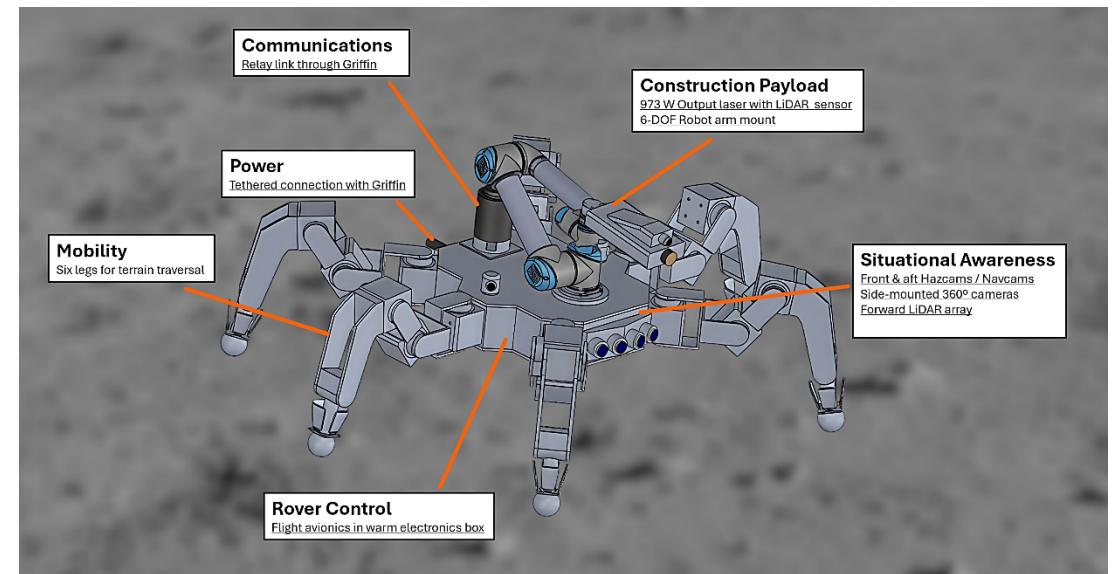
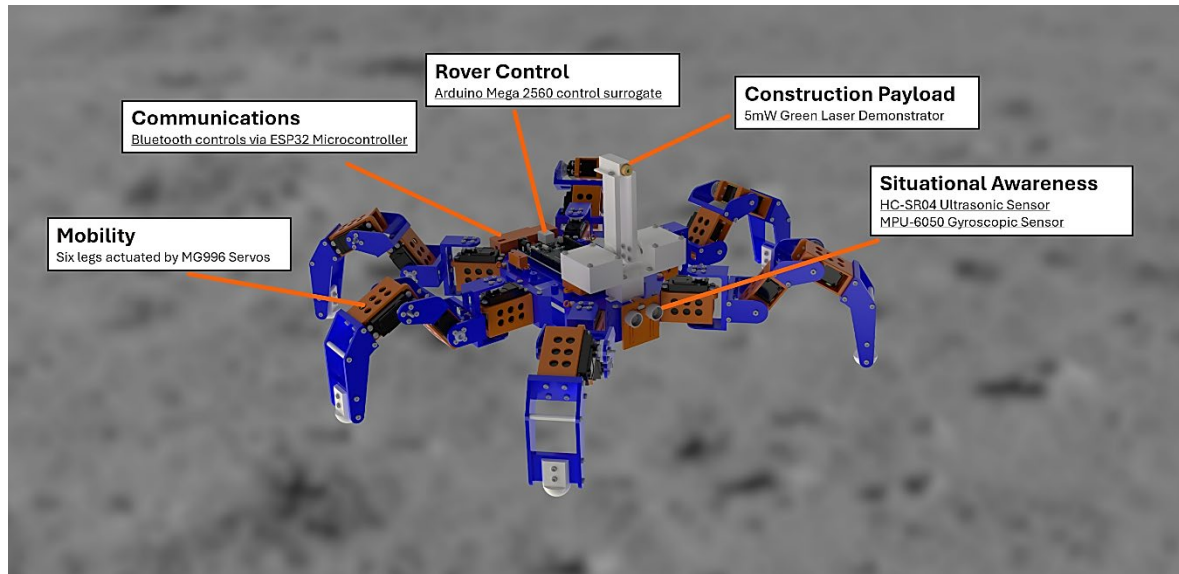
GN&C

- LiDAR sensors, hazcams, gyroscope, accelerometer,



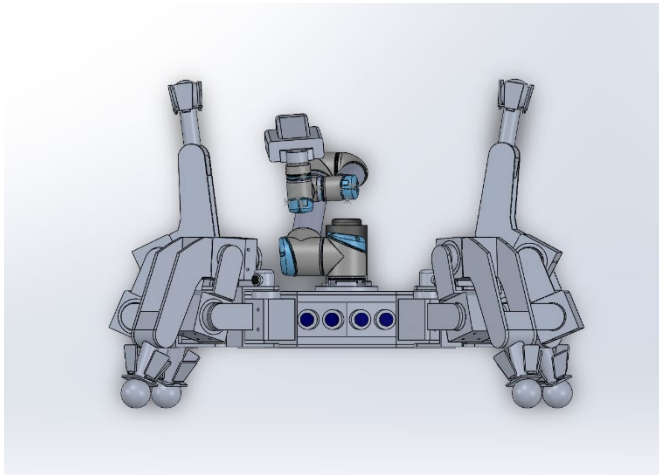
Two Side Angles of the LSRH

COMPARISON OF DESIGN AND PROTOTYPE

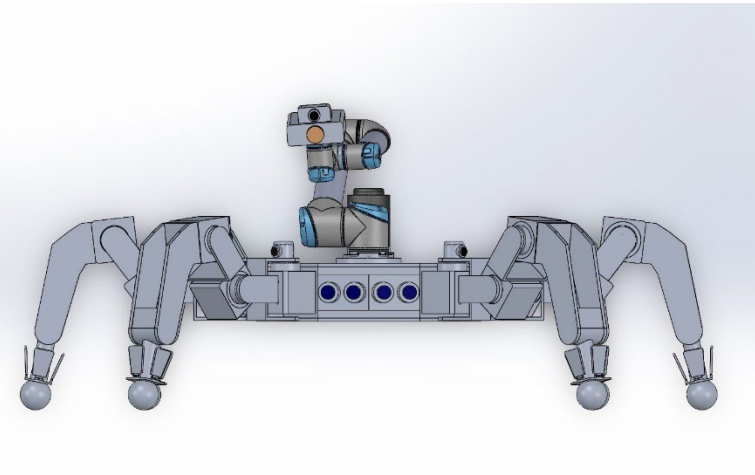


LSRH MISSION CONFIGURATIONS

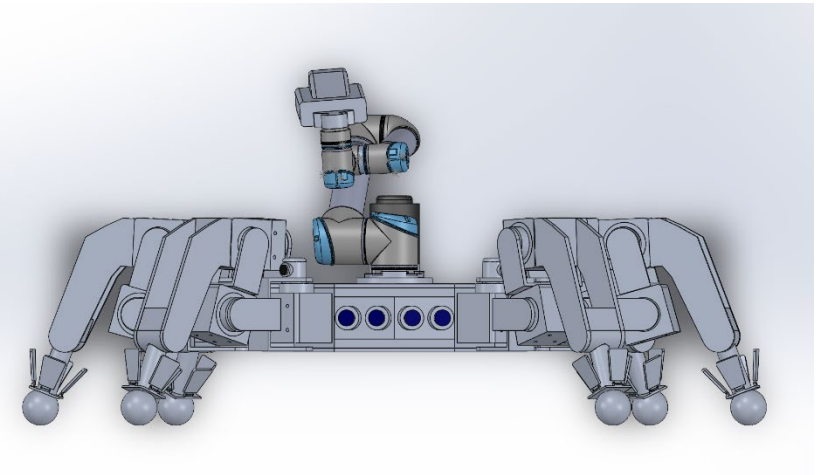
3 mission leg configurations:



Launch and Delivery Configuration



Standard (Walking) Configuration



Hibernation Configuration

LSRH MISSION CONFIGURATIONS

Table 5 Griffin Lander Constraints

Constraint	Volume	Mass	Power Provided	Communication
Value	1.7m x 1.75m x 2.5m	200 kg	5 kWe	5G relay 60 Mbps

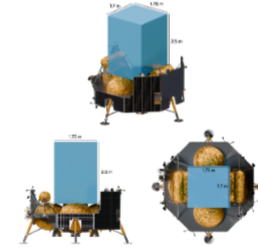
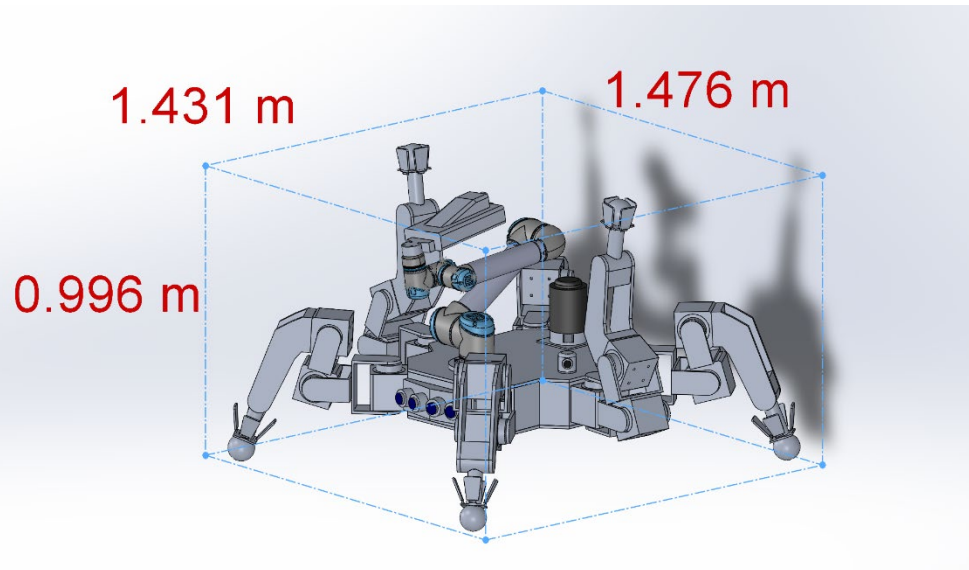
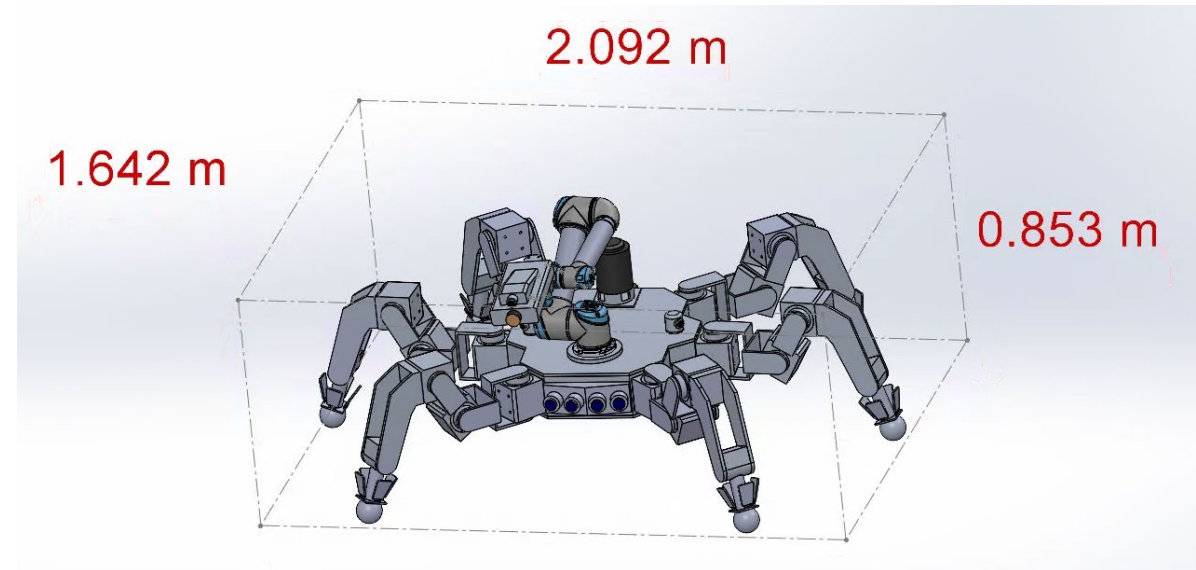


Fig. 4 Volumetric Constraints inside the Griffin Lander

The hexapod's volume profile is extremely flexible



Launch and Delivery Configuration



Walking Configuration

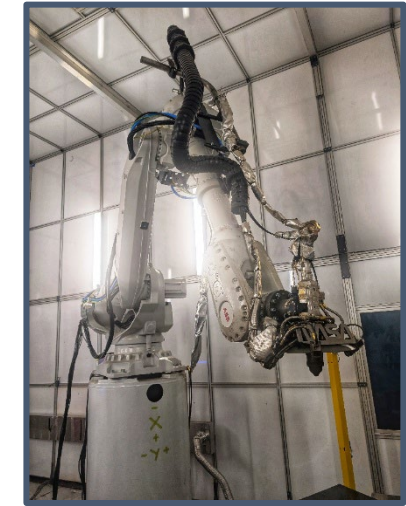
THE LSRH IS A COMBINATION OF ESTABLISHED SYSTEMS

Laser Sintering (MSFC)

- Laser sintering is being researched at MSFC
- Current tests have demonstrated up to **TRL 5** (dirty vacuum conditions), and have proven the capability to develop walls and other structures
- State of the art systems will require extreme amounts of time and power, two resources that are critical in the mission

Hexapod Lunar Exploration Concepts

- Hexapods and other novel robotic solutions are being considered by academia
- Inherent navigation advantages are attractive for lunar exploration
- Chiba University's COMET-4 hexapod robot weighs 2120 kg, demonstrating the feasibility of a large-scale hexapod system (10x the LSRH weight)



MSFC Laser Sintering Arm



Chiba University's COMET-4

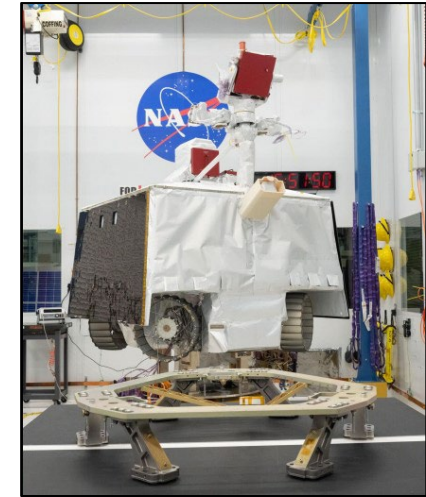
LSRH DESIGN CHOICES ARE DRIVEN BY NASA INITIATIVES

Volatiles Investigating Polar Exploration Rover (VIPER) and Perseverance Rover

- Novel dust mitigation strategies are utilized, **"socks" as flexible joint sealants** will be leveraged for the LSRH legs
- Sensor suites are inspired by Perseverance rover and VIPER

Dust Mitigation

- Regolith can contaminate joints, sensors, and laser optics during traverse and sintering
- Drives **sealed interfaces, protected optics, and dust-tolerant mechanisms;** as a part of NASA-STD-1008 compliance
- **Electrodynamic dust shields** using Indium Tin Oxide (ITO) electrodes (TRL: 8)
 - Example: MISSE-11 payload on the ISS



VIPER

Credit: NASA JSC & Advanced Cooling Technologies (VIPER)



VIPER "Sock"

Credit: NASA JSC & Advanced Cooling Technologies (VIPER)

LSRH DESIGN CHOICES ARE DRIVEN BY NASA INITIATIVES

Lunar Night

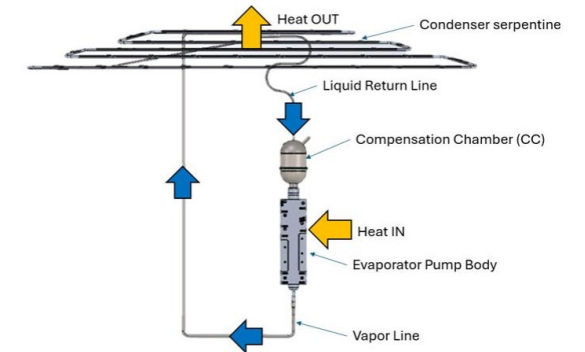
- Temperatures reach as low as $-215\text{ }^{\circ}\text{C}$ during the lunar night, which can last from ~ 2 days all the way to $\sim 2-3$ weeks; **hibernation cycles will be used**
- **Loop heat pipes**, like the VIPER's, will be utilized for systems that require heat
- The LSRH will enter a **low-profile hibernation stance** to near the lunar surface

Simulated LSRH Temperatures Using White Thermal Control Paint

Hot Case	$64.72\text{ }^{\circ}\text{C}$
Cold Case	$-197.47\text{ }^{\circ}\text{C}$

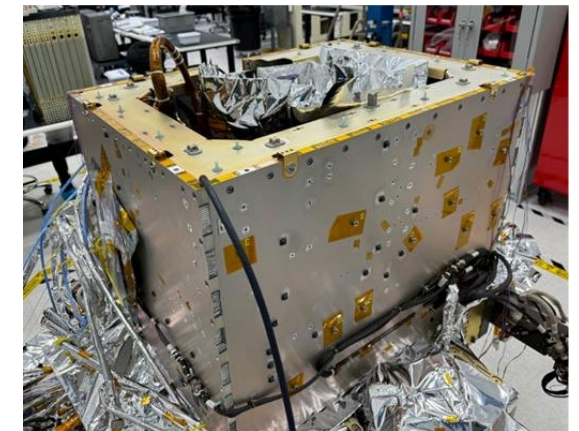
Minimum Power Required to Maintain Operational Temperatures

$0\text{ }^{\circ}\text{C}$	296.30 W
$-10\text{ }^{\circ}\text{C}$	255.55 W
$-20\text{ }^{\circ}\text{C}$	218.61 W



Loop Heat Pipe Schematic

Credit: NASA JSC & Advanced Cooling Technologies (VIPER)

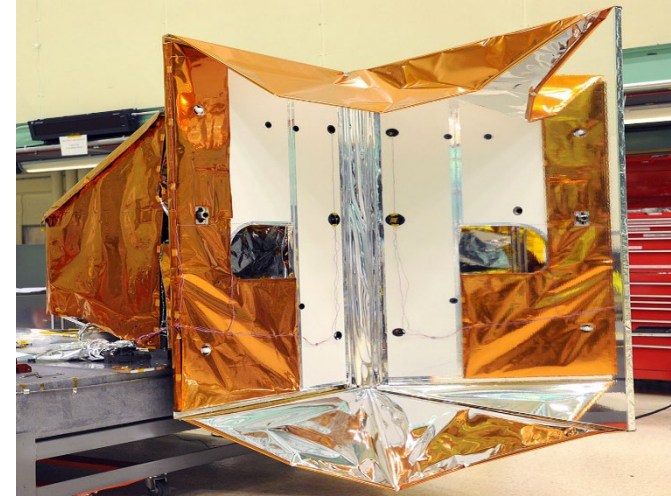


VIPER Heat Box

Credit: NASA JSC & Advanced Cooling Technologies (VIPER)

MATERIALS TAILORED TO OUR MISSION

- Structural Elements:
 - Aluminum alloys
 - Titanium alloys
- Protecting Sensitive Components:
 - Aluminized Kapton
 - Fiberglass cloth
 - Mylar multilayer insulation (MLI)
- Connective Elements:
 - Stainless steel, such as AISI 440C, for leg joints





THE BUDGETS DRIVING OUR DESIGN

Table 3 Preliminary Power Budget Before Laser Payload Considered

	Mobility (W)	Systems (W)	Total Power (W)	Total Power + 50% (W)
Low Consumption	300	200	500	750
Medium Consumption	300	300	600	900
High Consumption	300	400	700	1050

Table 7 Preliminary Mass Budget of Prototype and Flight Model

Prototype Total Mass	2.268 kg			
Total Flight Mass	178.503 kg (200 kg allowed)			
Subsystem	Structure	Sensors and Controls	Electrical and Computer	Payload
Prototype Subsystem Mass	77% (1.746 kg)	13% (0.294 kg)	5% (0.113 kg)	4.9% (0.131 kg)
Max Subsystem Allocated Flight Mass	154.08 kg	27.06 kg	11.93 kg	9.881 kg

3.4 TRADE STUDIES: LASER SINTERING DEVICE

Figure of Merit	Weight(%)	CO2 Laser	Fiber Optic Laser	Diode Laser
Sinter Efficiency	0.35	4	5	3
Sinter Quality	0.35	4	5	3
Fragility	0.15	2	4	5
Space Allocated	0.15	2	5	5
	1	3.3	4.8	3.7

- **Sinter Efficiency** - *How efficiently is input power converted to optical/output power?*
- **Sinter Quality** - *How optimized is the laser for operation at high output powers?*
- **Fragility** - *How likely will the laser be damaged during transit and operating environments?*
- **Space Allocated** - *How much space is needed to contain the laser and all accessory components?*

3.4 TRADE STUDIES: PAYLOAD INTEGRATION

Figure of Merit	Weight(%)	Integrated on Front of Body	Robot Arm Mounted	Belly Mounted
Working Range	0.6	2	5	1
Design Complexity	0.15	4	2	5
Laser Protection	0.15	2	5	1
Power Required	0.1	5	1	5
	1	2.75	3.95	2.2

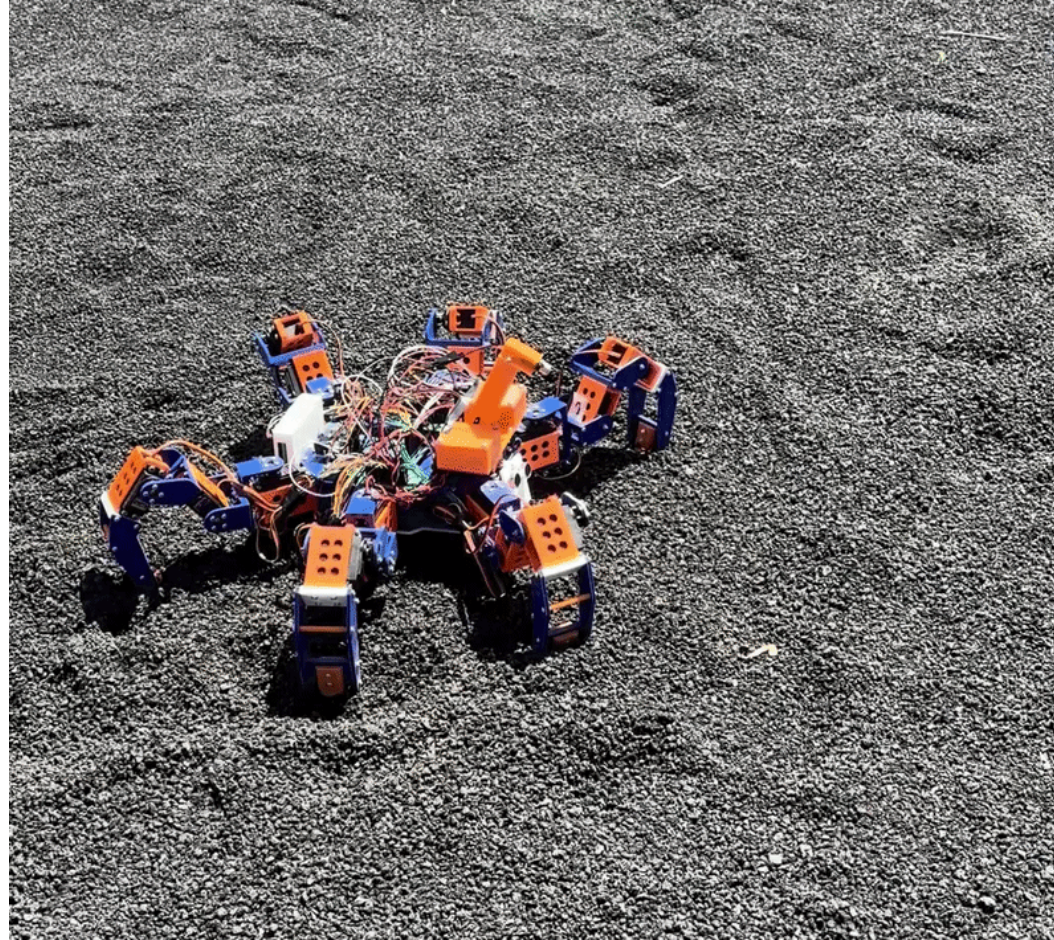
- **Working Range** - *How far can the laser be used from the rover?*
- **Design Complexity** - *How feasible is the design?*
- **Laser Protection** - *How will the laser stay protection and housed?*
- **Power Required** - *Other than the laser, what other power is required?*

2.1 EXECUTION OF CONCEPT DESIGN



2.1 EXECUTION OF CONCEPT DESIGN

Step 4: Initiate Sintering Process



*1DOF arm vs. 6DOF arm

2.1 EXECUTION OF CONCEPT DESIGN

Enter Hibernation



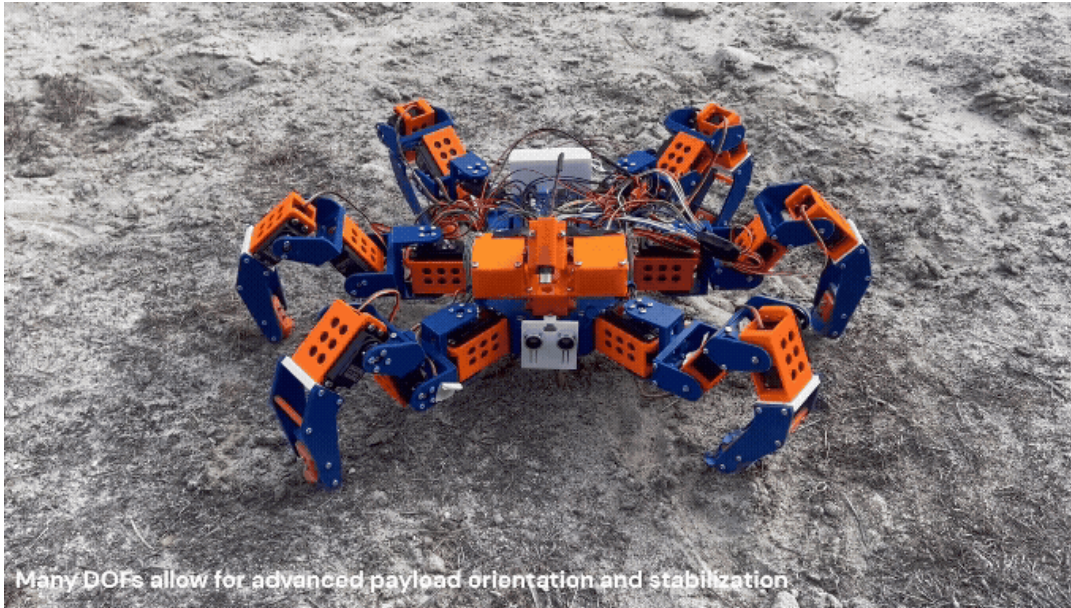
Exit Hibernation



2.1 EXECUTION OF CONCEPT DESIGN

MANEUVERING ABILITY

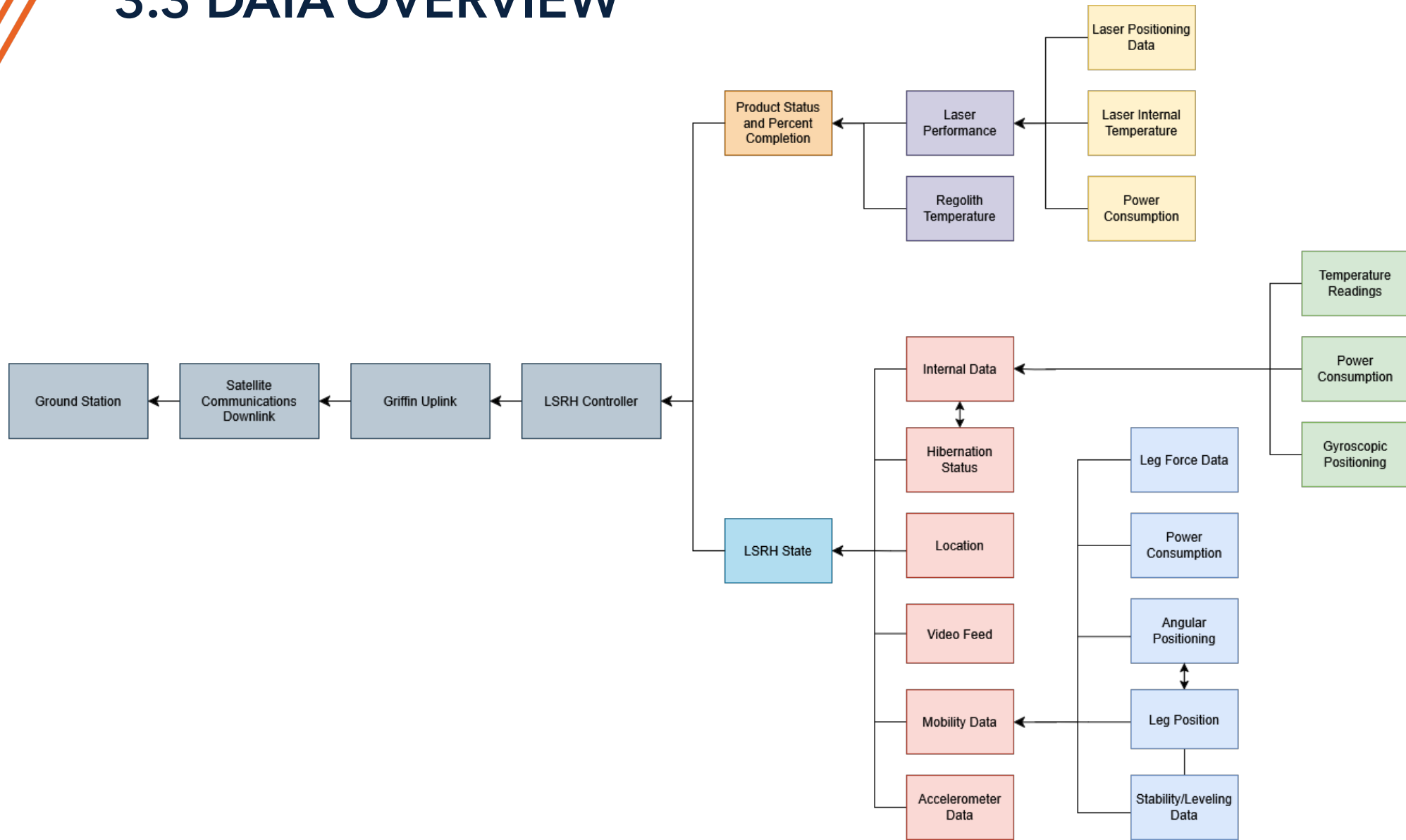
Rotation Capabilities



Turning in Place



3.3 DATA OVERVIEW





DETAILED SYSTEM DESCRIPTIONS



HEXAPOD MOBILITY SYSTEM

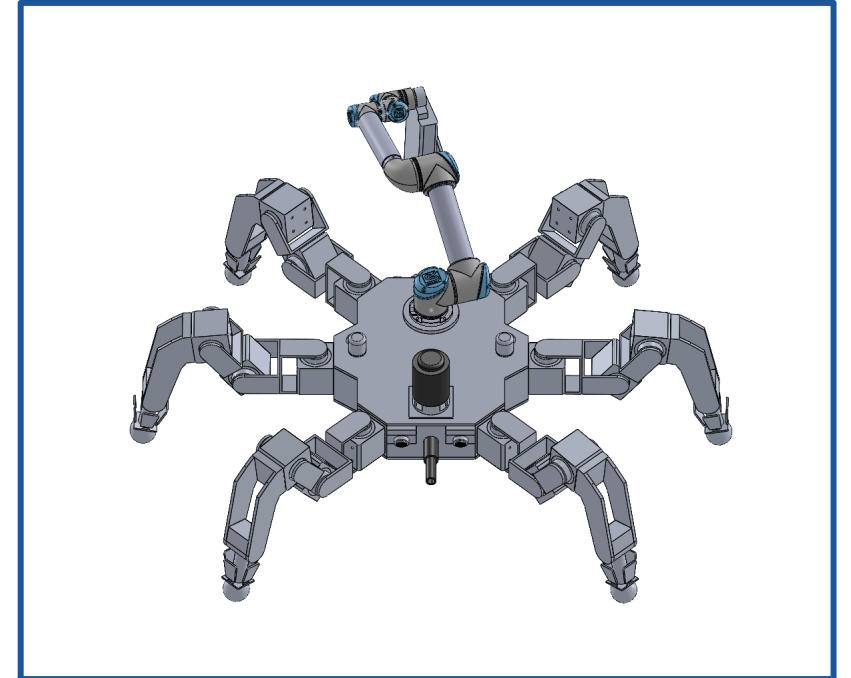
HEXAPOD MOBILITY IS THE ENABLING SUBSYSTEM

System Overview

- Six-legged propulsion system: 18 servos, controlled by the central computer, total of 24 degrees of freedom
- Mobility system enables stable positioning for sintering and terrain traversal

Unique Aspect

- Hexapod system is the key unique aspect, being a six-legged configuration; introduces need for inverse kinematics algorithms and complex programming
- Many degrees-of-freedom allow the system to self-stabilize and compact itself for transport
- Complex obstacle avoidance is possible, AI-powered simulations will be leveraged to create the autonomous capabilities



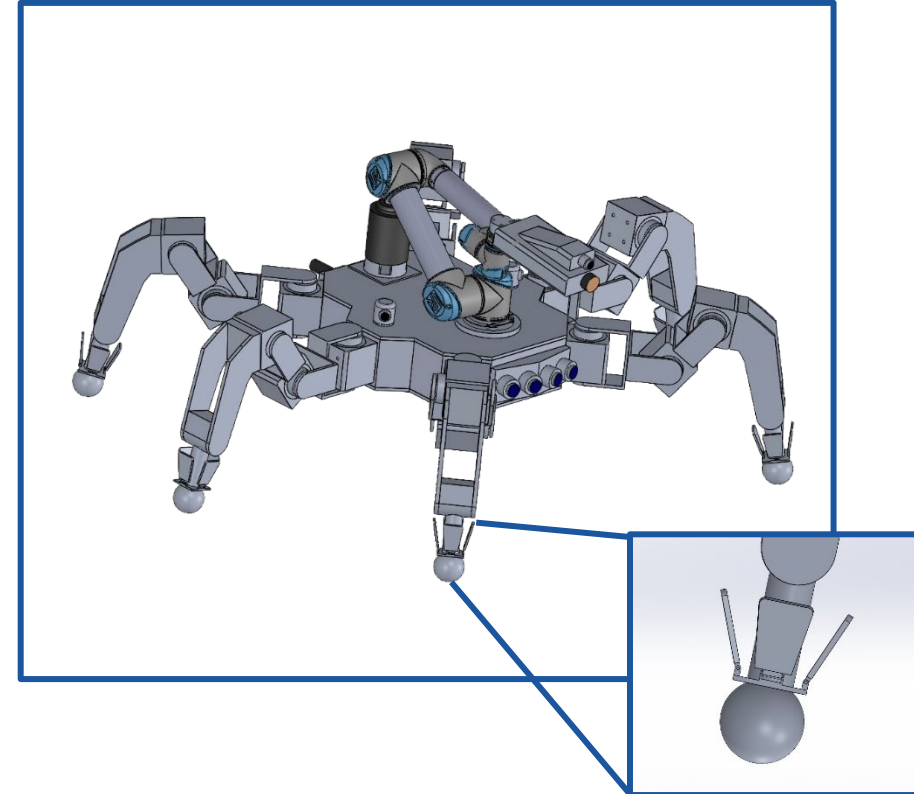
HEXAPOD MOBILITY IS THE ENABLING SUBSYSTEM

System Requirements

- Derived from the mission requirements of navigating rough, sloped lunar terrain while carrying and positioning the sintering payload
- Power dedicated to the mobility system must also be conserved to allocate as much power as possible to the laser system

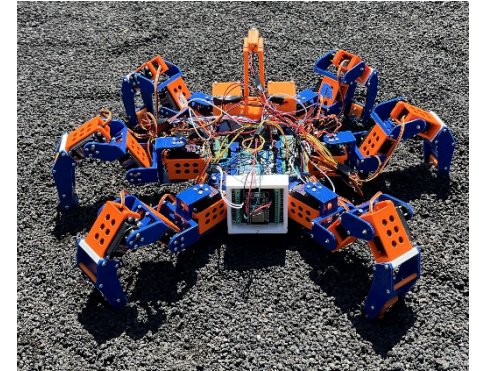
Constraints

- Constraints arise from slopes at the South Pole average at 7° - 8° , with maximum slopes ranging from 27° - 41°
- Moon quakes occur from thermal shocks during transitions from lunar night; anticipated effects are low-impact but drive the hexapod's vibration stability requirements

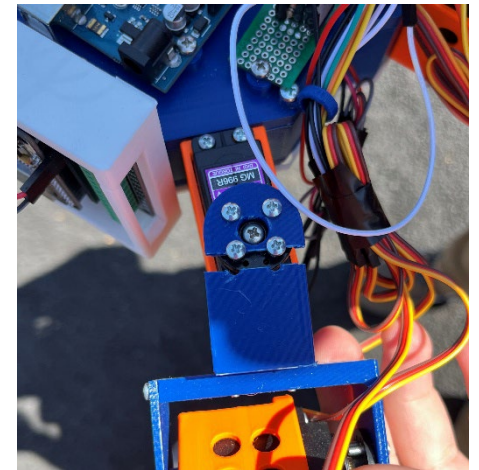


LESSONS LEARNED FROM MSFC LRT TEST

- When immobilized on flat terrain, the hexapod could clear the obstruction and continue moving
 - Automation at this stage of development might be difficult; required eyes on recognition of the obstruction and what movements were necessary to get unstuck
 - AI could be used to identify when the hexapod is stuck and what movements would be needed to resume mission
- When immobilized on sloped terrain, the hexapod suffered a failure
 - Material failure occurred at the joint of the back right leg due to regolith accumulation when moving downslope
 - This added stress caused a shearing failure of the PLA plastic joint
 - Using stronger materials, this failure mode could be avoided along with modifications to the gate motion and wider foot contact area (enabled by the spring-loaded design)
- Lack of dust mitigation measures contributed to a failure
 - Servo became jammed when hexapod was moving downslope
 - The movement of large clumps of regolith caused the stirring up of dust which got lodged into the servo, causing failure
 - Implementing dust socks and enclosing circuitry will prevent dust from harming critical components



LSRH at the MSFC LRT



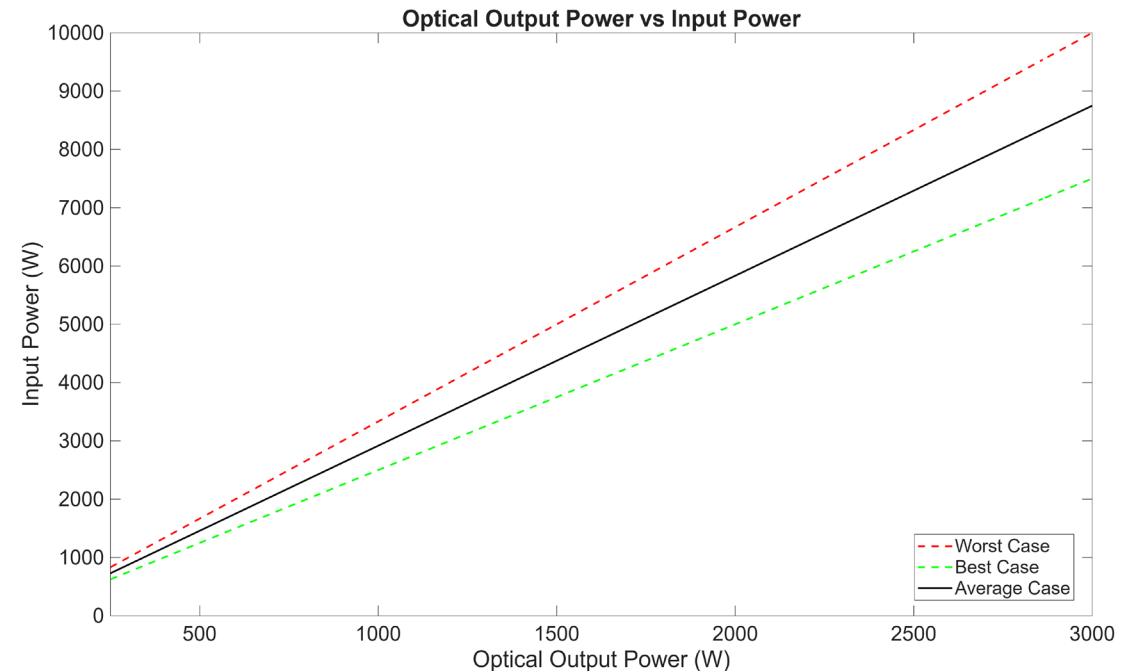
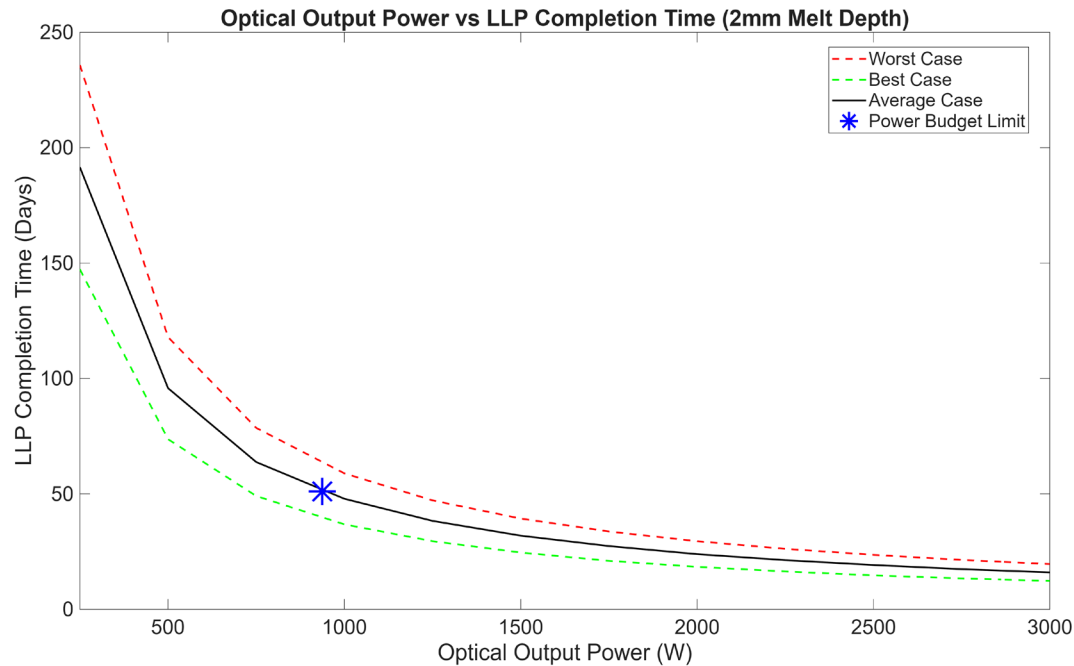
PLA Failure



LASER SINTERING SYSTEM

HIGH LASER OPTICAL POWER REDUCES SCHEDULE

- **1 meter width** hexagonal tiles to be used for construction
- **18-meter LLP requires 245 tiles**
- Cases derived from surface energy density at 2mm melt depth





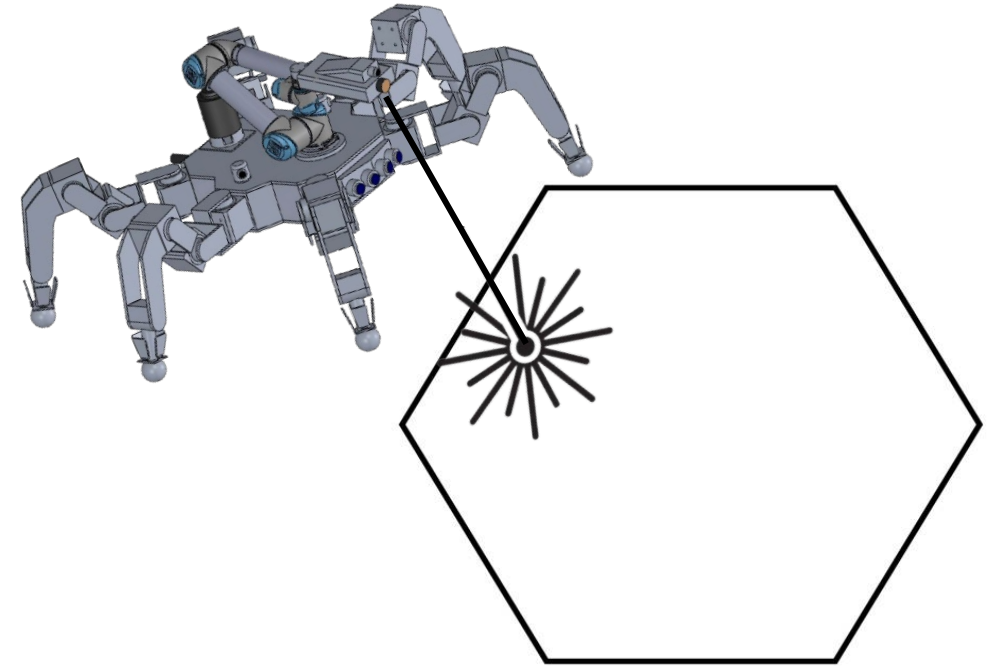
POWER BUDGET CONSTRAINS LASER OPTICAL POWER

- Power budget limits the payload to **2733 W of input power**
- This corresponds to a laser with **937 W of output power**

P_{out} (W)	937
P_{in} (W)	2733
Time to Complete a Tile (hrs)	5.01
Launchpad Completion Time (Earth days)	51.1
Energy to Complete a Tile (kWh)	14.13
Total Energy Consumption (kWh)	3352

ENERGY AVAILABILITY PREVENTS NIGHT OPERATIONS

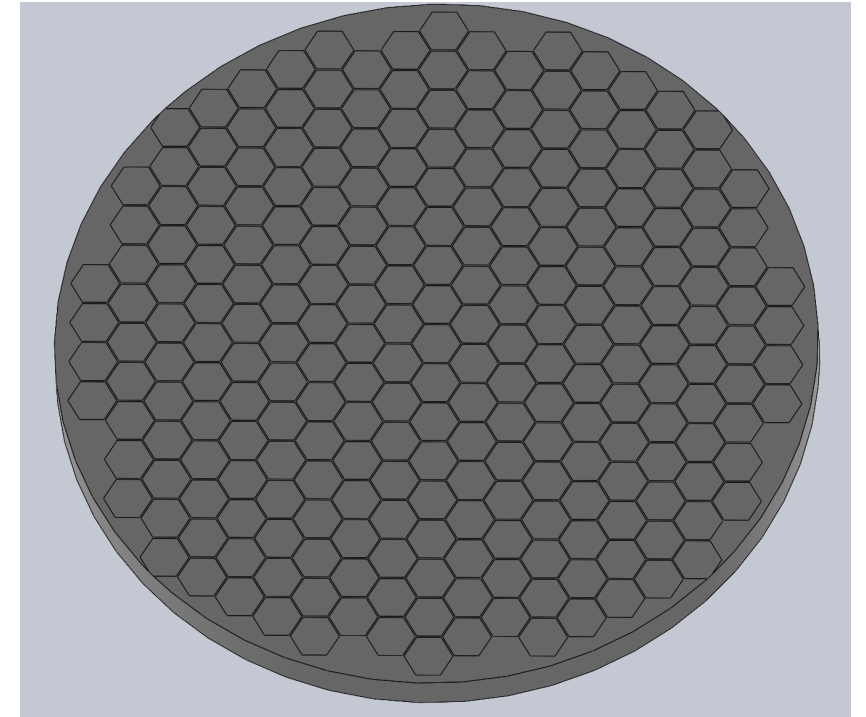
- 14kWh needed to complete a single tile
- Laser operations cease at lunar night due to 8kWh limit
- Upwards of 4.7 MWh needed to construct entire LLP



*** Note that these figures represent the laser payload only, not the overall system energy consumption*

NOMINAL TIMELINES CONTAIN APPROXIMATIONS

- LLP completion in less than 30 Earth days for output powers greater than 1500W
- Power budget limits construction time to a minimum of **51 Earth days**
 - *With lunar night limitations and maintenance cycles, these numbers are expected to be larger*



Honeycomb-Patterned LLP

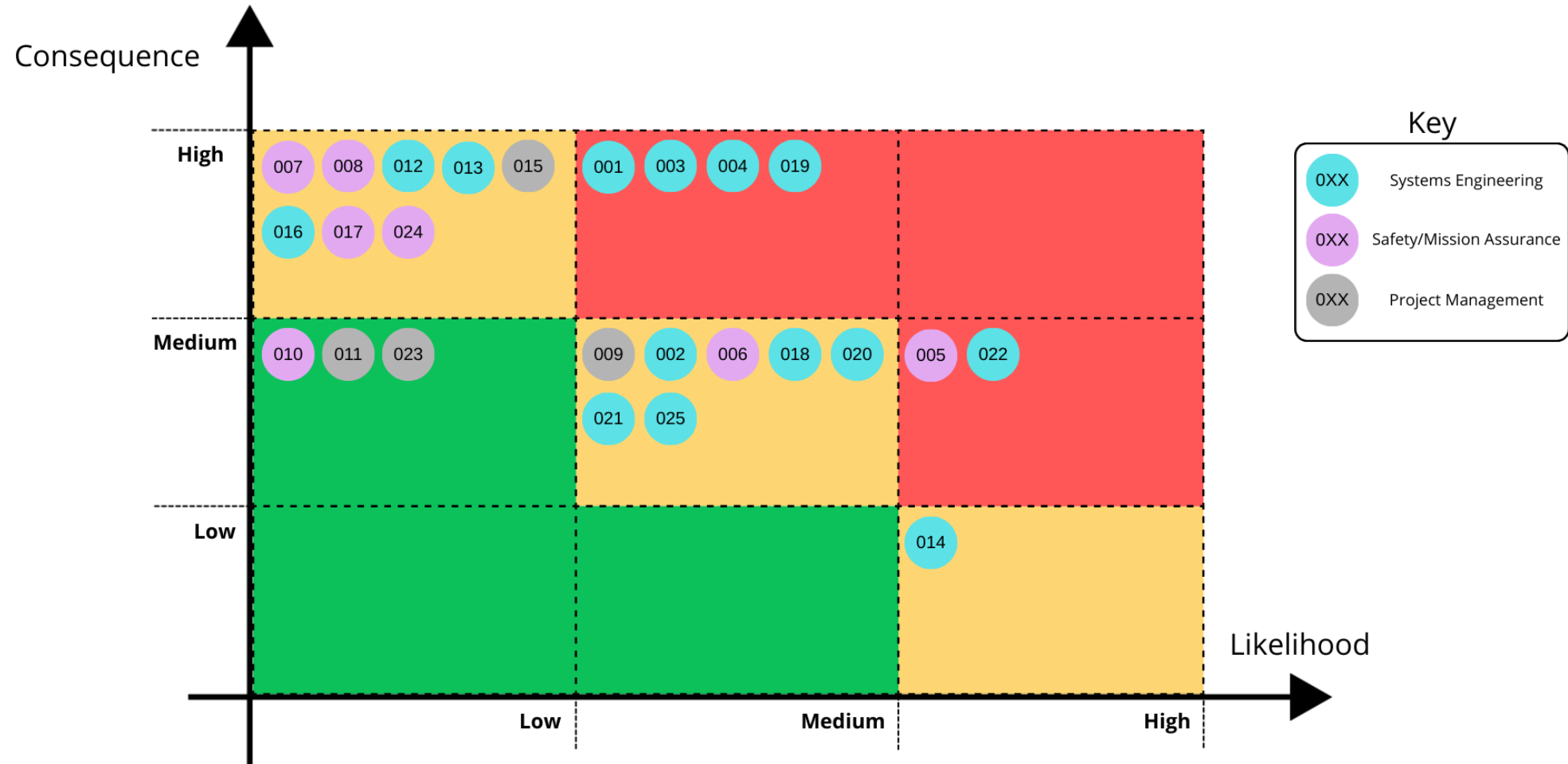


RISK ASSESSMENT

3.2 A MEDIUM-RISK MISSION WITH POTENTIALLY HIGH REWARD

Critical Risks	Mitigation Strategy
LSRH-R-019: Laser optical system misalignment	Mitigate risk: <ol style="list-style-type: none">1. Vibrations testing2. Quality testing/assurance
LSRH-R-022: Regolith on moon differs meaningfully from the regolith simulants available on Earth	Accept risk: LSRH design must conform to a range of expected values for material properties rather than specific individual values
LSRH-R-002: Trip on or otherwise become entangled in the tether power cable	Mitigate risk: <ol style="list-style-type: none">1. Construction of boom2. Light amount of tension will be applied to the tether3. AI tools will be employed to train the LSRH mobility system on Earth in freeing itself from several potential entanglement scenarios

3.2 A MEDIUM-RISK MISSION WITH POTENTIALLY HIGH REWARD

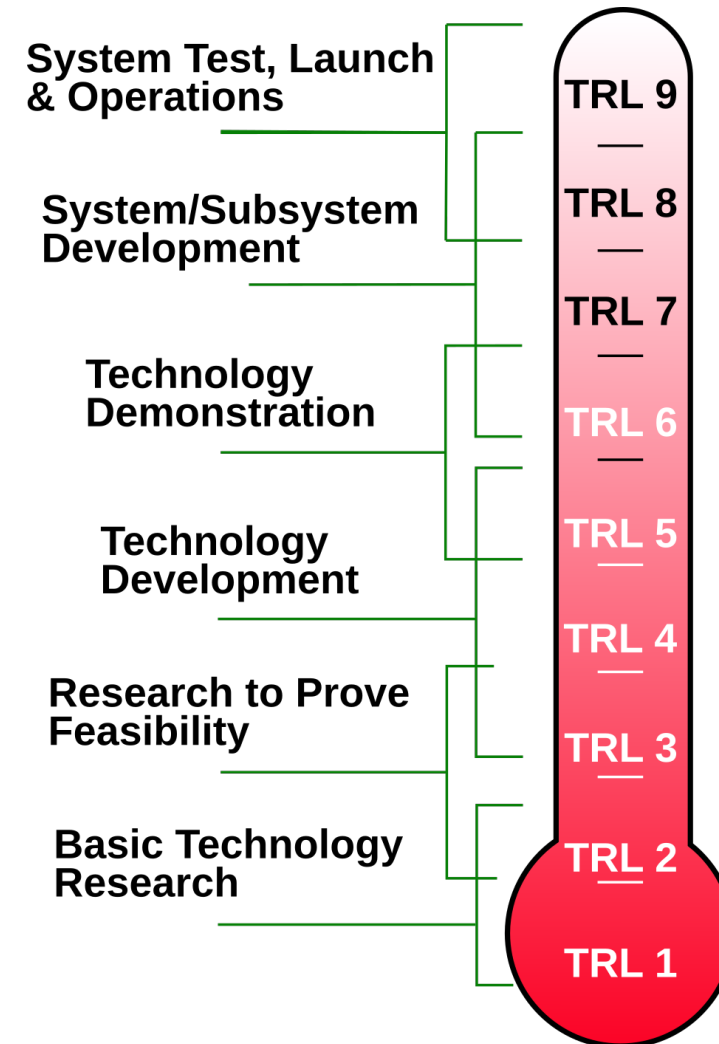




PROJECT PROGRESS AND NEXT STEPS

CURRENT TECHNOLOGY READINESS LEVELS

- Overall system Readiness
 - LSRH [Level 3]**
- Subsystem Readiness
 - Hexapod Mobility [Level 3]
 - Communications [Level 5]
 - Thermal Systems [Level 3]
 - Power Systems [Level 3]
 - GN&C Systems [Level 3]
 - Laser Sintering Payload [Level 5]



1.2 PROJECT NEXT STEPS: BILL OF MATERIALS

Item (from preliminary WBS)	Cost (millions \$)
Project Management	10
Systems Engineering	30
SMA	30
Science/Tech	80
Payload	60
Spacecraft	10
Mission Ops	10
LV/Services	200
Ground Systems	10
Systems Integration & Testing	25
Education and Public Outreach	5
Total	470
Total + 50%	705

2.2.2. Task 5: Select Cost Estimating Methodology

The goal of this task is to select the most appropriate cost estimating methodology (or combination of methodologies) for the data available to develop a high-quality cost estimate (Figure 5).

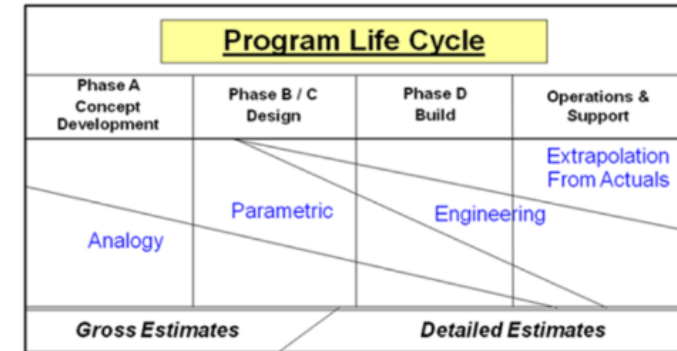


Figure 5. Use of Cost Estimating Methodologies by Phase¹²

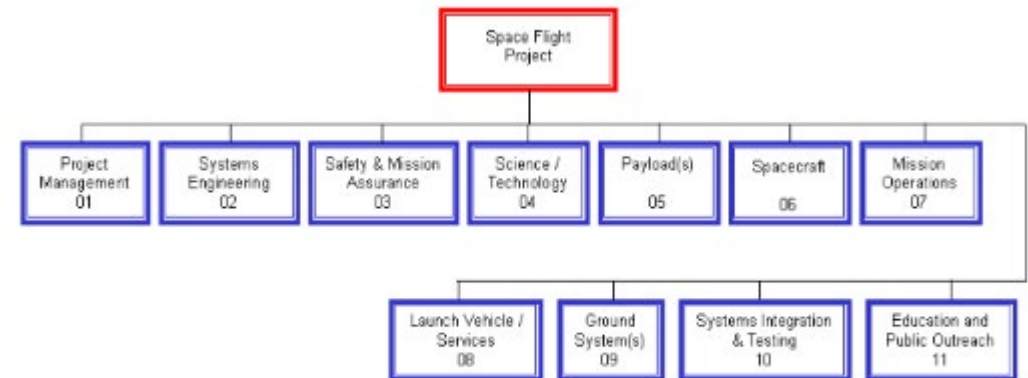


Figure 4. Standard Flight Project Level 2 Work Breakdown Structure⁷

1.2 PROJECT NEXT STEPS: MANUFACTURING AND TESTING

- Numerous tests are required for launch and space operations (standards listed as appropriate):

Mechanical

Test	Standard
Strength	NASA-STD-5001
Sinusoidal Sweep	-
Random Vibrations and Acoustics	NASA-STD-7001
Shock	NASA-STD-7003
Mechanical Function	-

Thermal/Electrical

Test	Standard
Thermal Vacuum and Ambient Pressure Thermal Cycle	-
Thermal Balance	-
Bakeout/Outgassing	-
Leak	-
EMI/EMC	MIL-STD-464

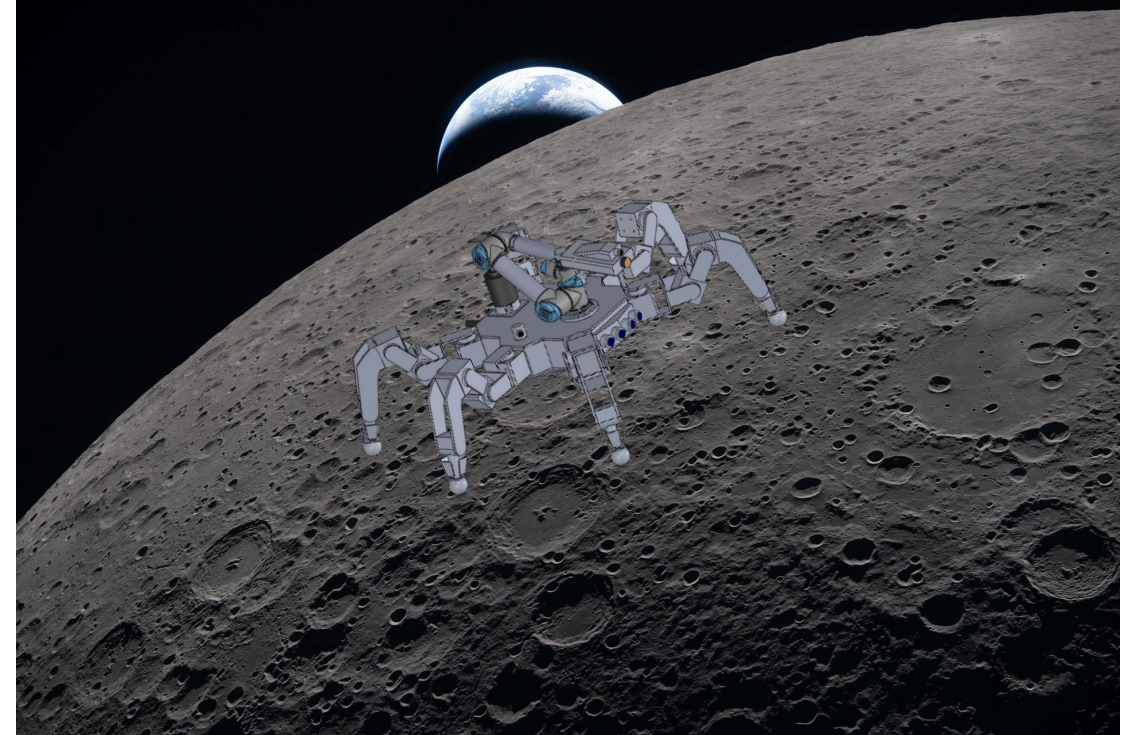
Functional

Test	Standard
Electrical Interface	-
Comprehensive Performance	-
Failure-free Performance	-
End-to-End Compatibility	-
Mission Simulations	-
Life Test Program	-
Mass Properties Verification	-
Alignment	-

*Taken from NASA-STD-7002B: Payload Test Requirements

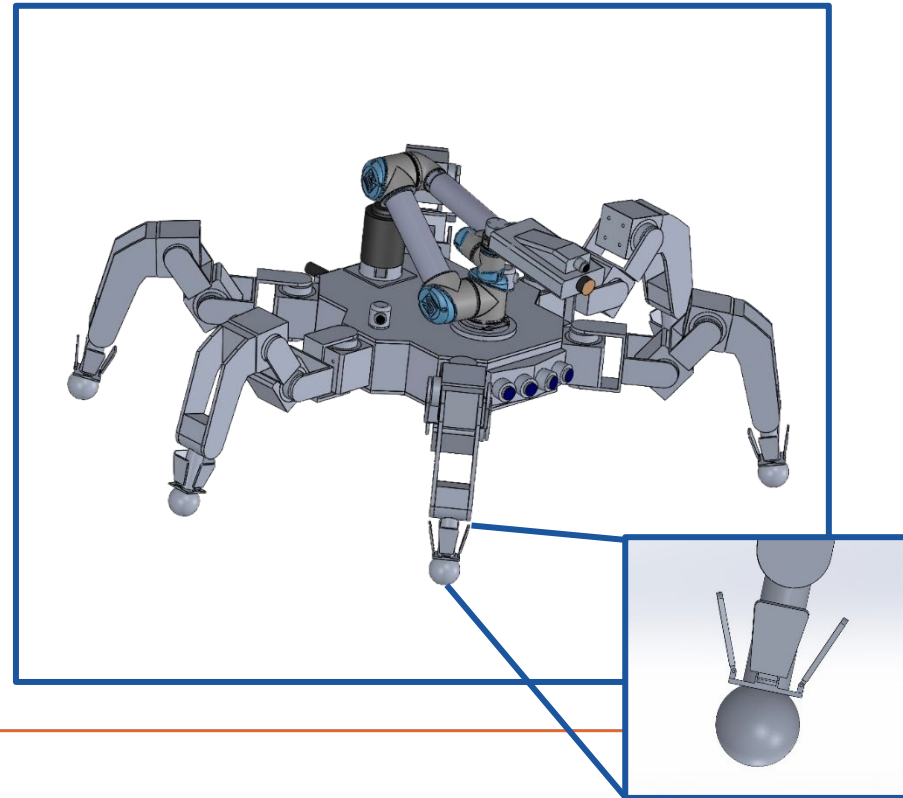
2.3 PROJECT NEXT STEPS: PATH TO PDR

- Detailed R&D Plan
- Continuous Cost Estimation/Budget Changes
- End of Life Operations Plan
- Peer Reviews
- Software Development
- Heavy Involvement with Laser SMEs and Industry Partners
- Detailed Lunar Environment Impact Study
- Detailed Sub System Architecture



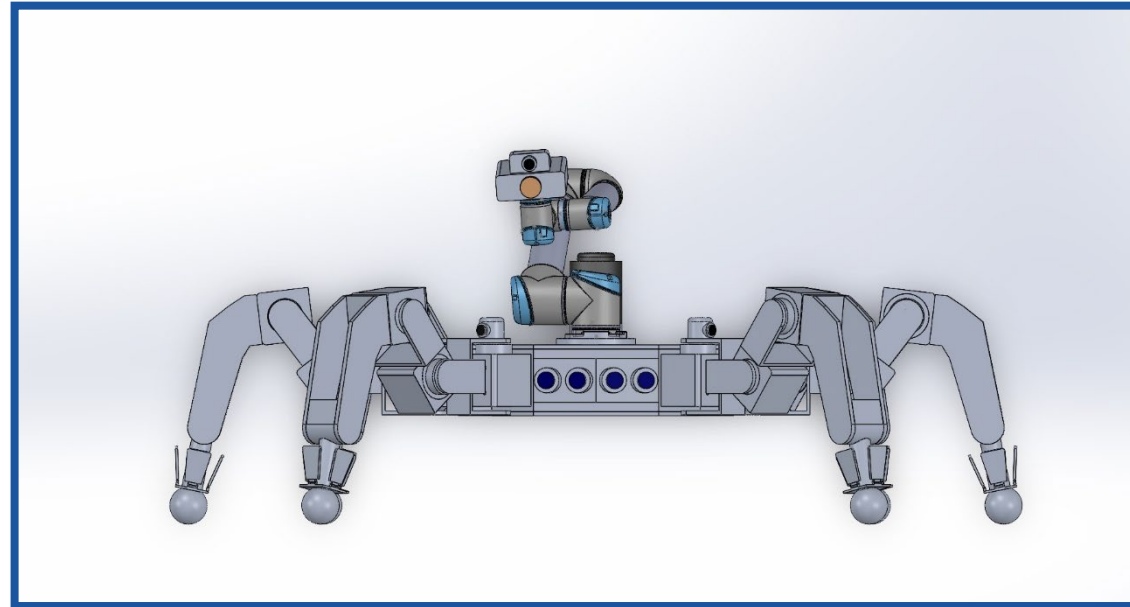
4.1 MOST INNOVATIVE IDEAS

1. Large-scale incremental laser sintering of lunar launch/landing pads
2. Hexapod mobility system for lunar operations
3. Two-part foot design, ball foot tip with spring-loaded "snowshoes"



4.2 MOST IMPORTANT TECHNOLOGIES TO DEVELOP

1. Laser sintering technology
2. Hexapod mobility system technology
3. Large source of continuous power



4.3 OUR BIGGEST CHALLENGES SO FAR

1. Finding or creating a large enough continuous source of power for laser sintering operations
2. Prototype development: gait development and refinement, embedded systems integration, assembly and manufacturing-focused design
3. Quantifying laser sintering performance such that the design could move forward with confidence





CONCLUSION



A MISSION TO DIRECTLY SUPPORT LUNAR OPERATIONS

The LSRH Design

- Hexapod rover with laser sintering capabilities
- Hexapod mobility chosen to verify the technology on the lunar surface
- Fiber optic laser sintering chosen for power consumption and performance

Key Design Choices

- Hexapod mobility
- Dust mitigation socks¹
- Hibernation period¹
- Incremental LLP construction method
- LiDAR sensor included
- Tethered power connection

¹ VIPER mission

Moving Forward

- Design adheres to lunar and Griffin Lander constraints
- Construction of one LLP is feasible given these design choices
- R&D period is preferred to potentially significantly reduce mission time



QUESTIONS?

Acknowledgements: Dr. Davide Guzzetti, Matt Anderson, and Jeremiah Tyrrell



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