2022 Breakthrough, Innovative, Game-Changing (BIG) Idea Challenge

November 14-17, 2022

http://bigidea.nianet.org/

The BIG Idea Challenge is sponsored by NASA's Space Technology Mission Directorate (Game Changing Development Program) and Office of STEM Engagement (Space Grant), and managed by the National Institute of Aerospace.

WORMS Field-Reconfigurable Robots for Extreme Lunar Terrain

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PASADENA, CA, NOVEMBER 14-17, 2022

1: Carnegie Mellon University
2: University of Denver
3: Florida Tech

SPACE RESOURCES WORKSHOP

Massachusetts Institute of Technology

WORMS

Walking **O**ligomeric **R**obotic **M**obility **S**ystem

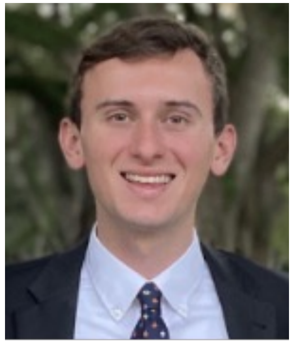
Field-reconfigurable robots to meet all types of lunar surface mobility needs

Introducing our presenters

George Lordos
PhD Candidate
Year 6
AeroAstro

Team lead

Introduction & overview



Michael Brown
SM Candidate
Year 2
AeroAstro

Deputy team lead

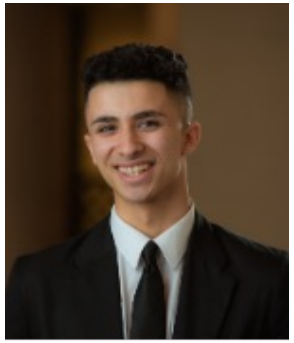
System arch., path to flight

Cesar Meza
Undergraduate
Class of 2025
AeroAstro

Mechanical design & testing

Fatema Zaman
Undergraduate
Class of 2025
EECS

Electrical design & testing



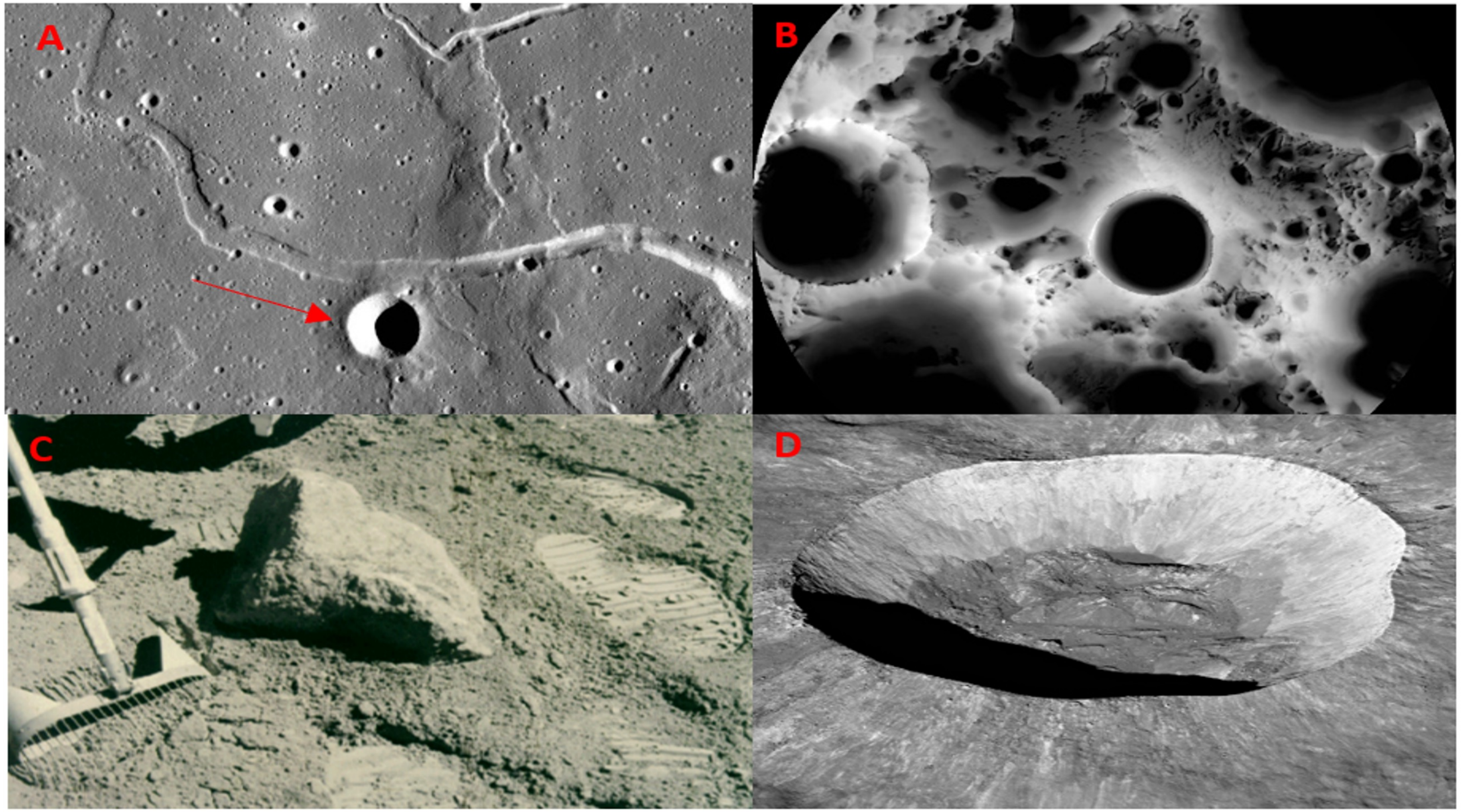
Jacob Rodriguez
Undergraduate
Class of 2024
AeroAstro

Software design & testing

Brooke Bensche
Undergraduate
Class of 2023
AeroAstro

Use cases and future impact

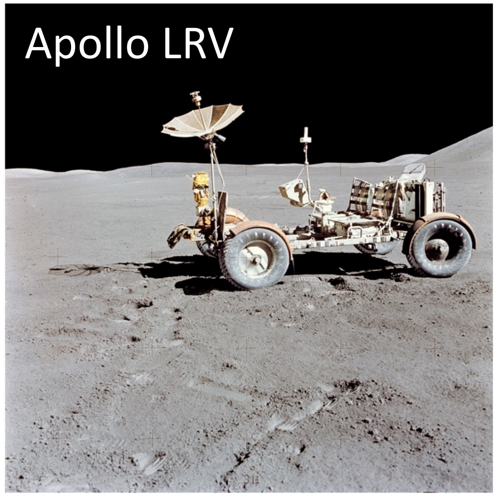
Extreme terrain access will be essential for lunar exploration

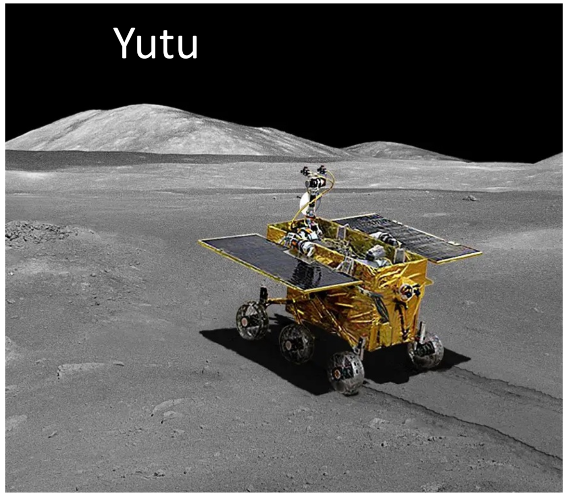


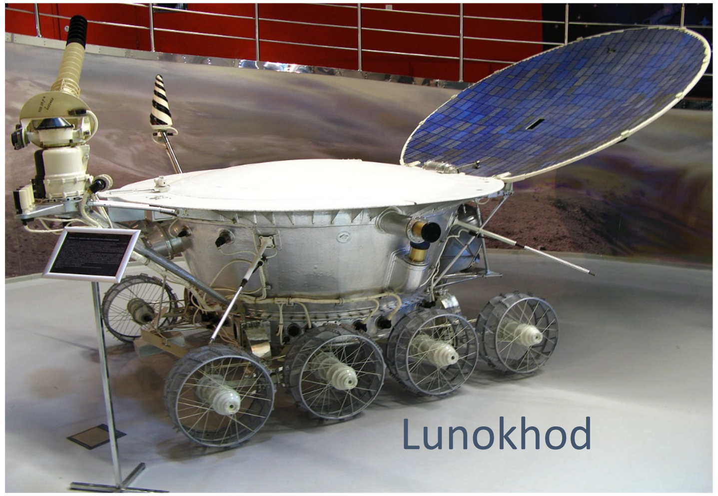
A) Lava Tubes, Caves and Pits
C) High Porosity Regolith

B) Permanently Shadowed Regions
D) Steep and Uneven Terrain

New mobility solutions are needed for extreme terrain







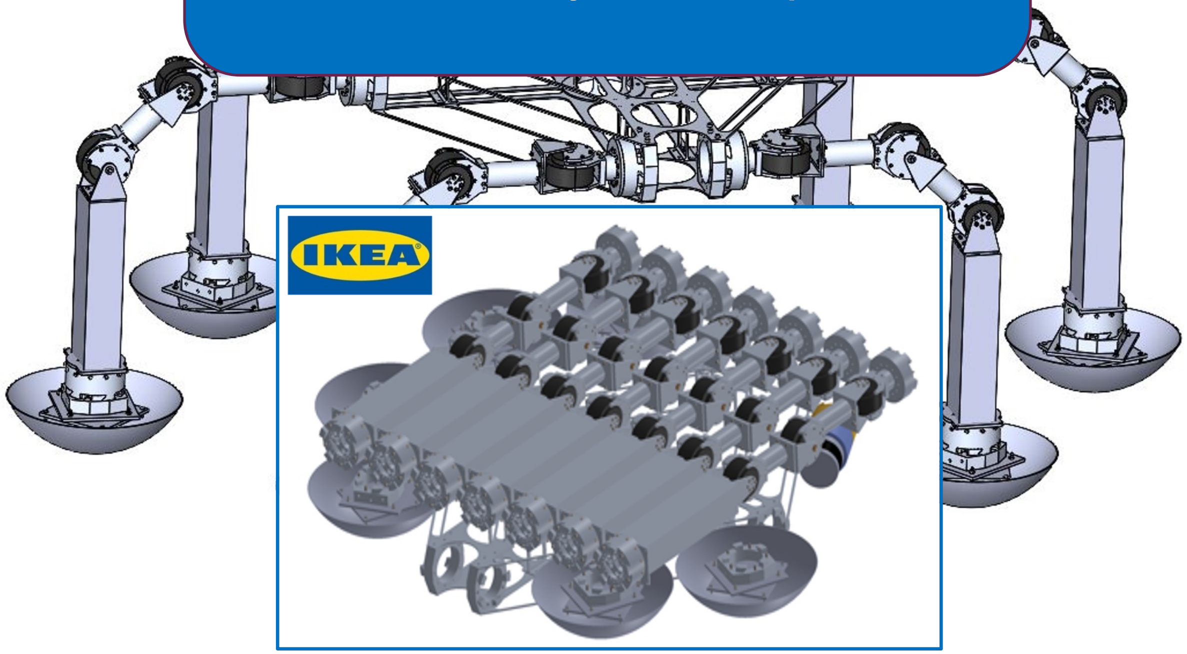
Presentation Roadmap

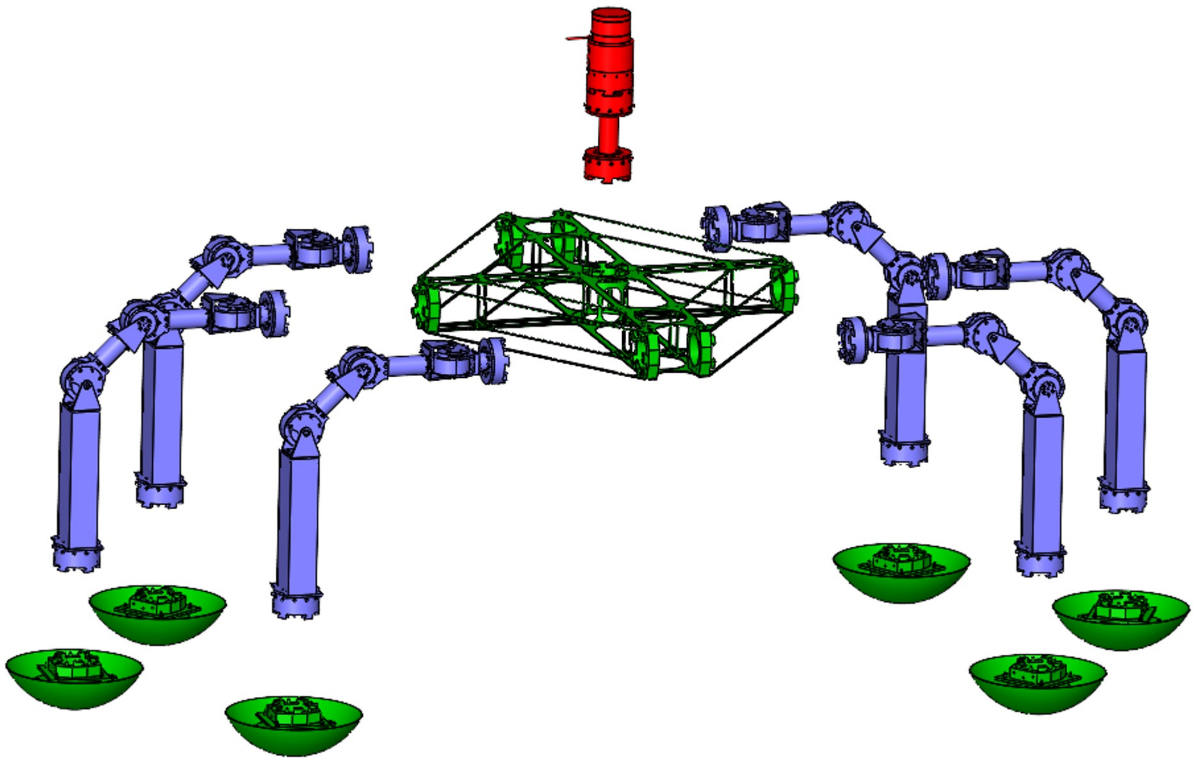
- WORMS Platform Architecture
- Design, Development, Testing, and Engineering
- Path to Flight
- Roadmapping the Future of WORMS

WORMS Platform Architecture

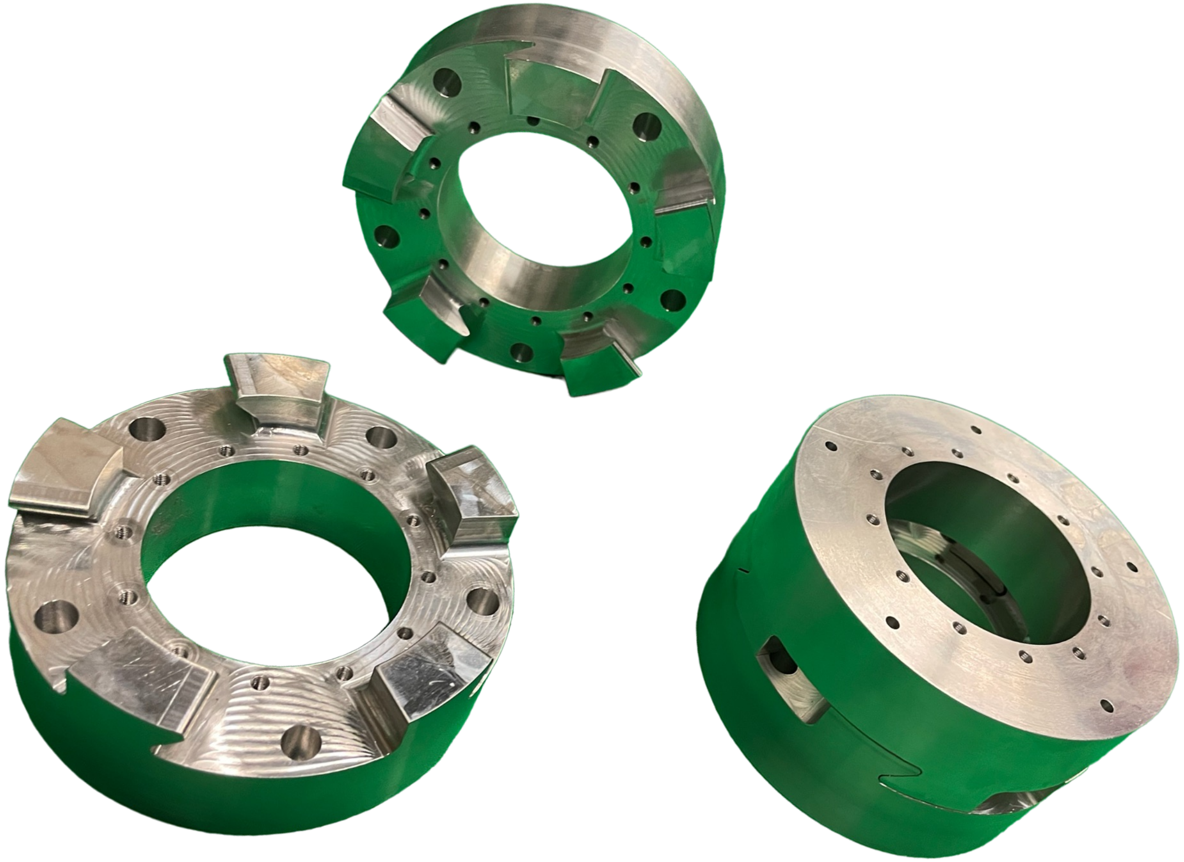
WORMS: a platform for field-reconfigurable robots

IKEA analogy: flat pack for shipment to a new location, easy to assemble by a non-specialist





Fundamental architecture element: Universal Interface Block

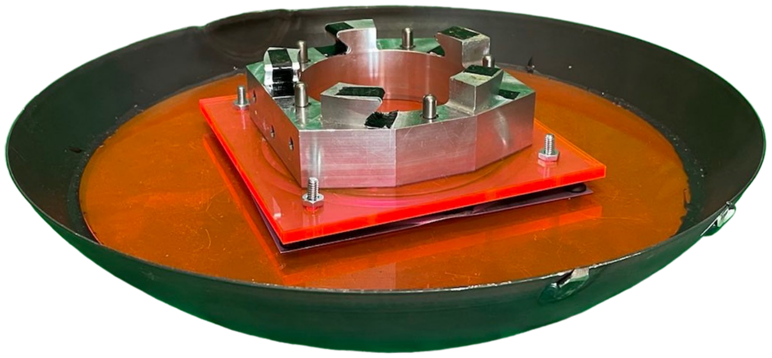


Every element in WORMS has at least one Universal Interface Block (UIB).

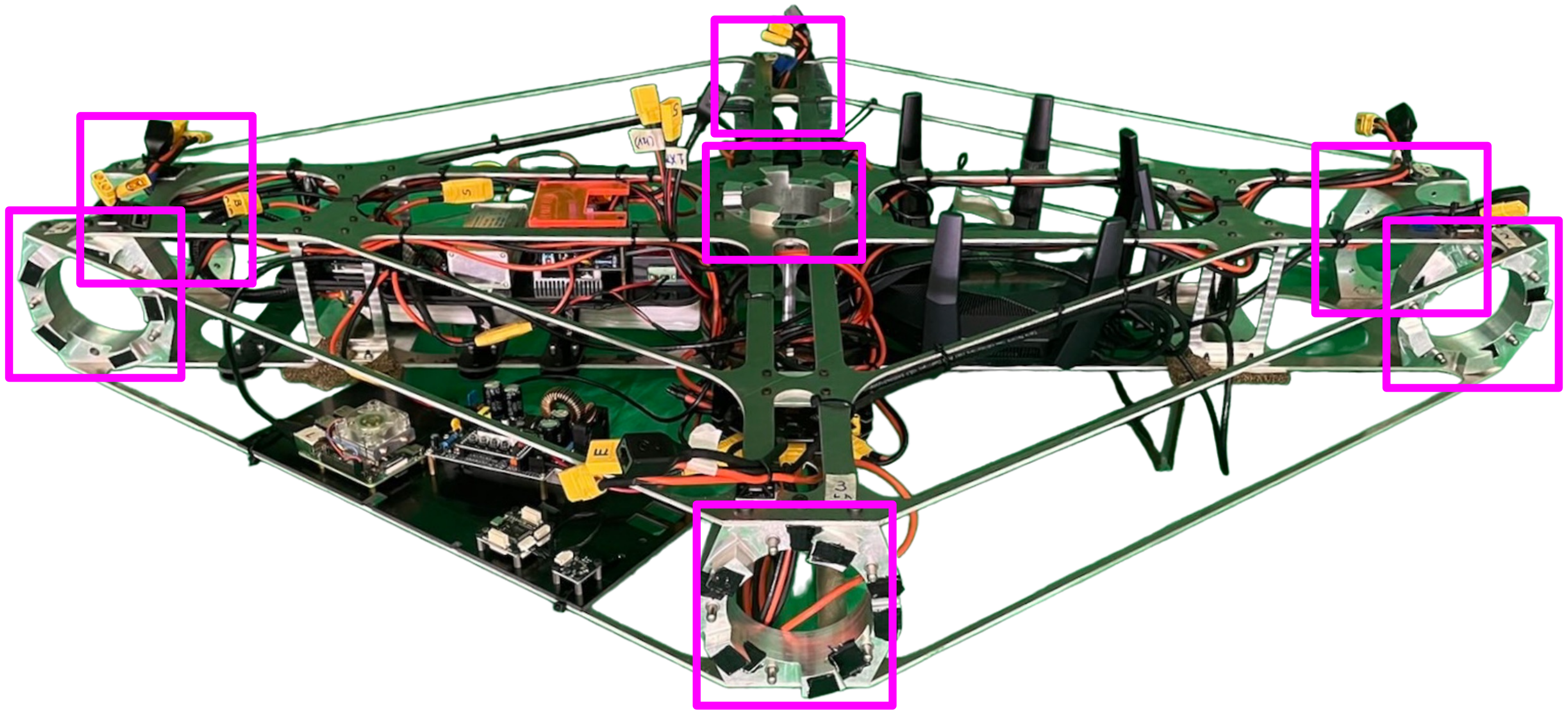
Architecture elements: Worms

Each Worm is an identical, self-contained robot with actuators, sensors and a battery.

Architecture elements: simple accessories (e.g. shoes, a pallet)



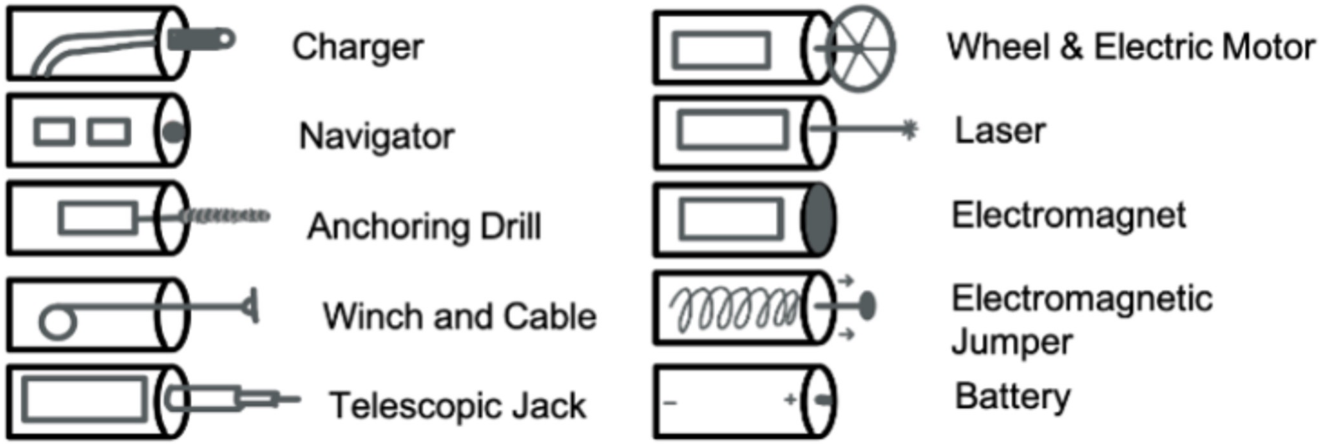
Rounded Shoe with UIB Connector



Pallet with 7 UIB Connectors and power sharing capability

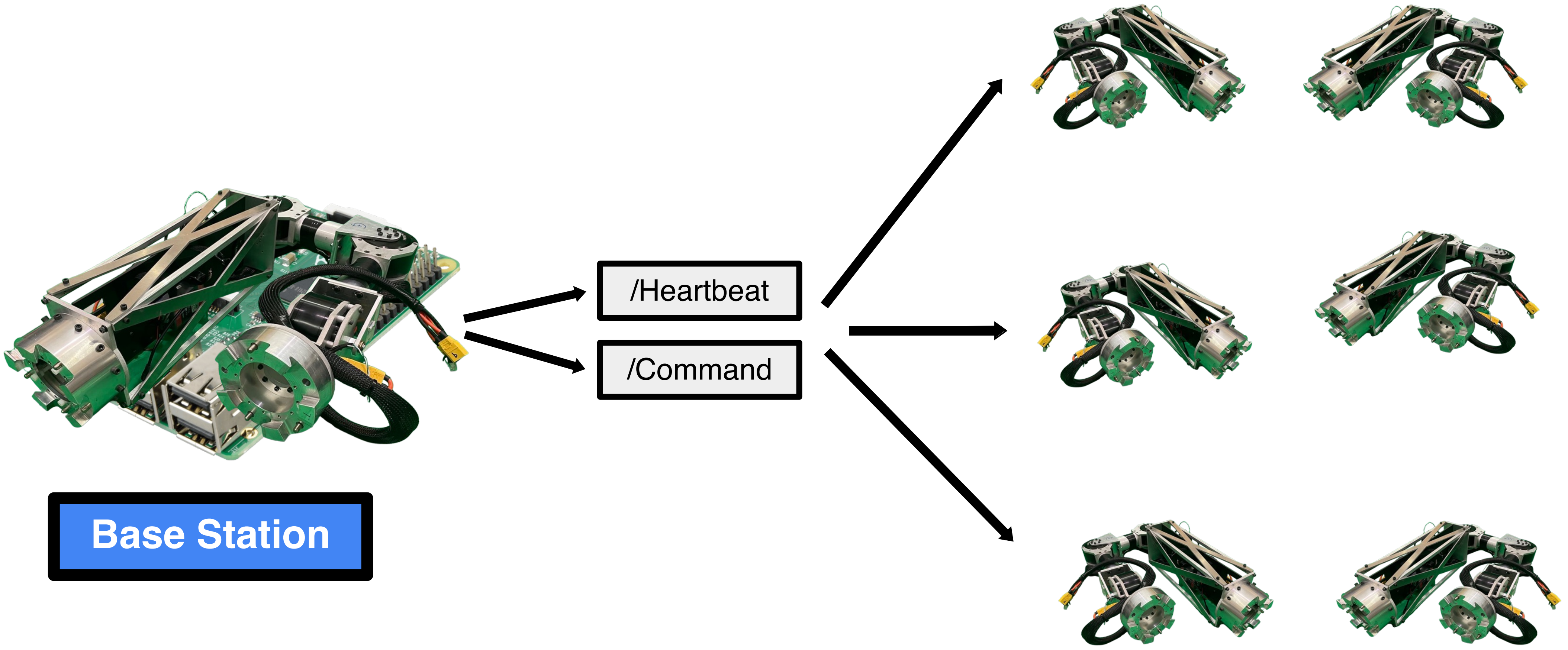
Architecture elements: sophisticated Species Modules

The "mapper" Species Module, with a LiDAR unit on top and a UIB Connector at the bottom.

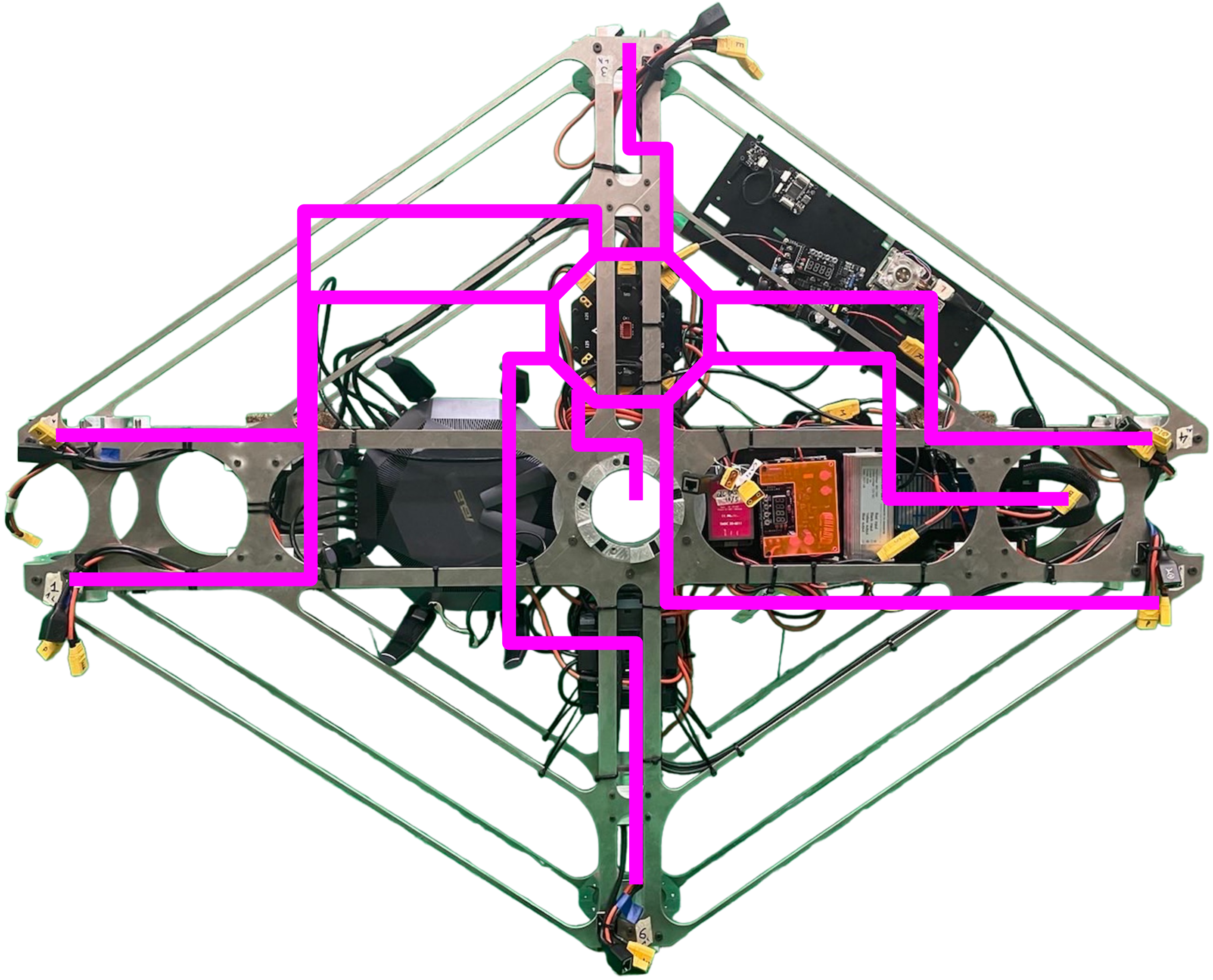


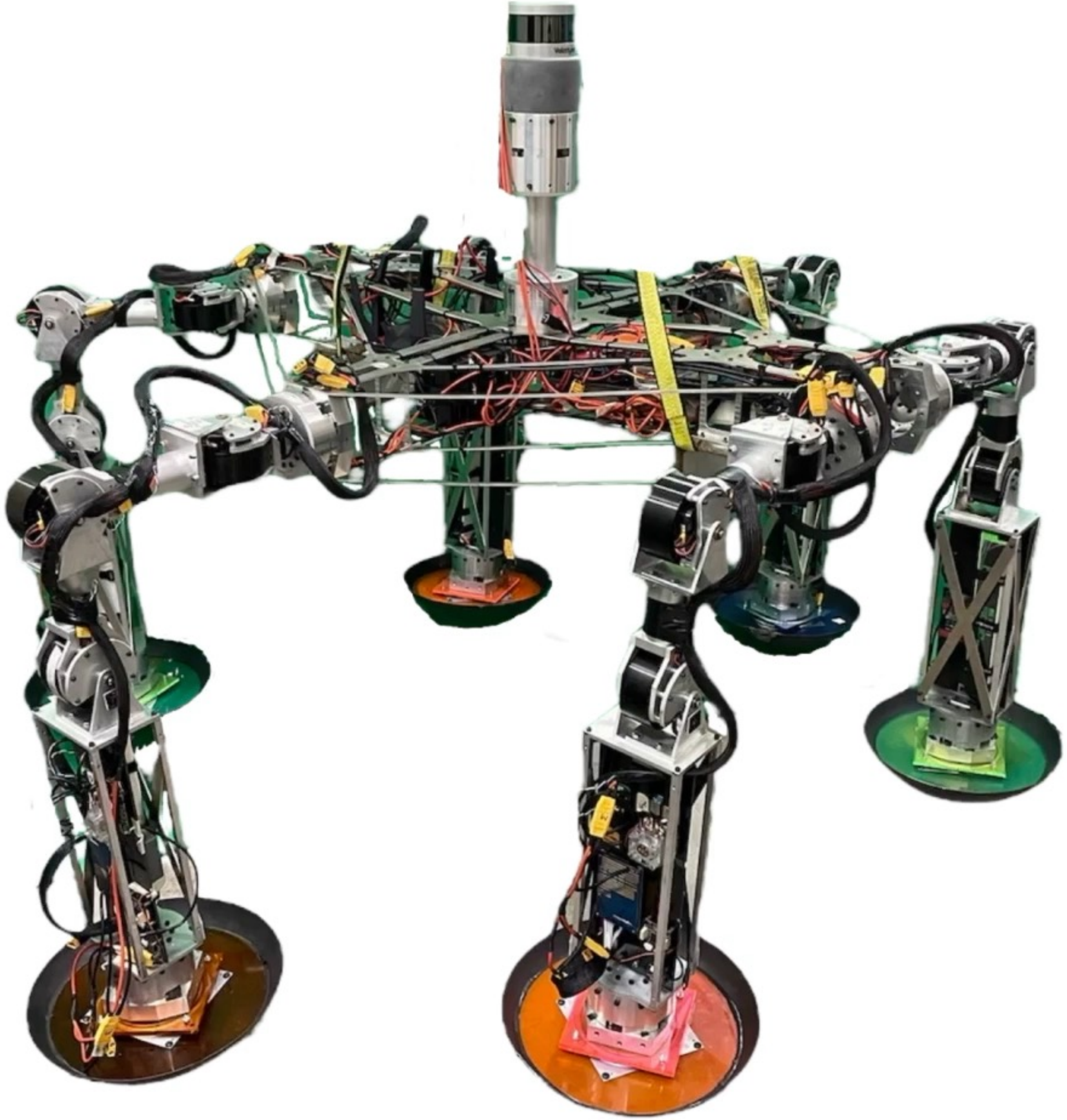
Countless Species Modules can specialize Worms for a multiple kinds of missions.

Architecture elements: Multi-Agent Software



Architecture elements: Power Sharing



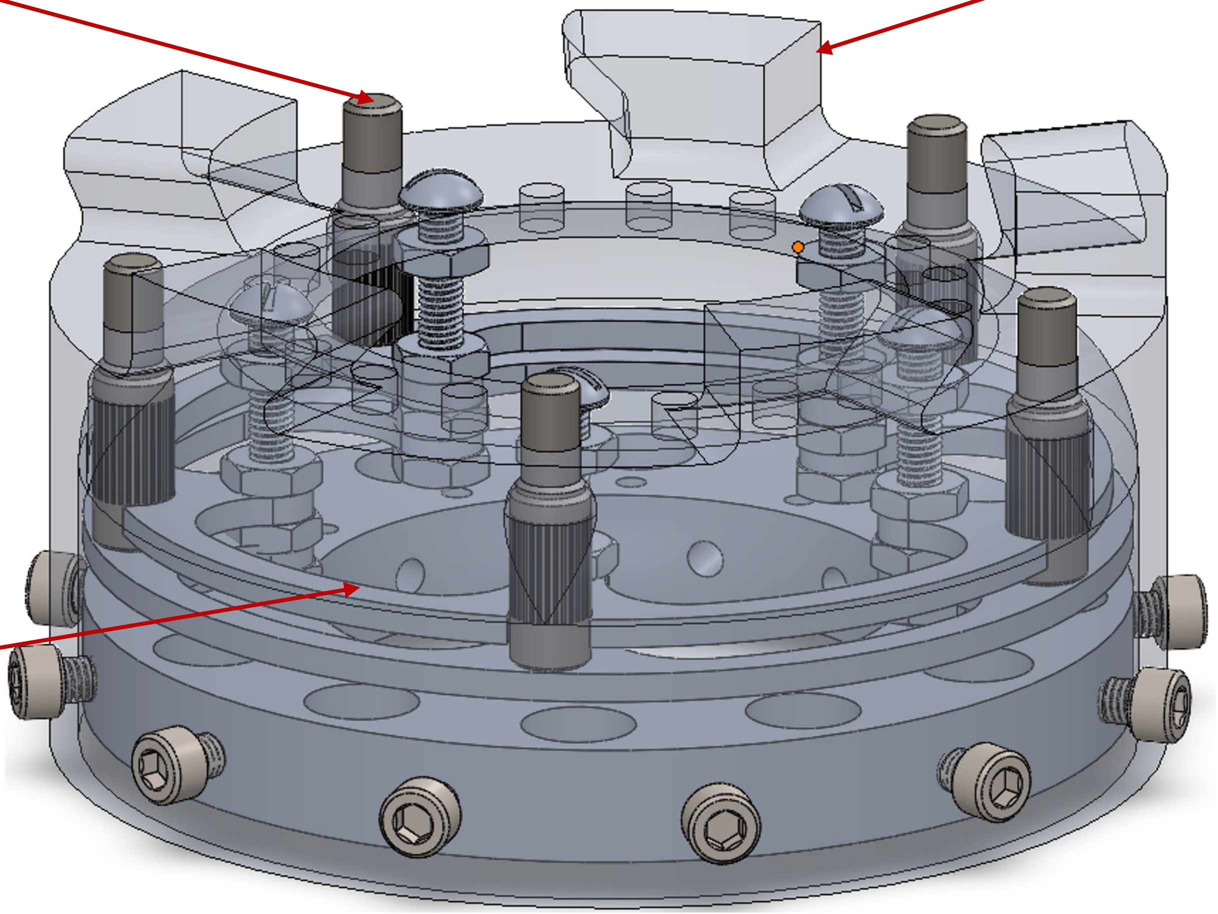


WORMS Design, Development, Testing and Engineering

UIB: an interface for a robust mechanical connection

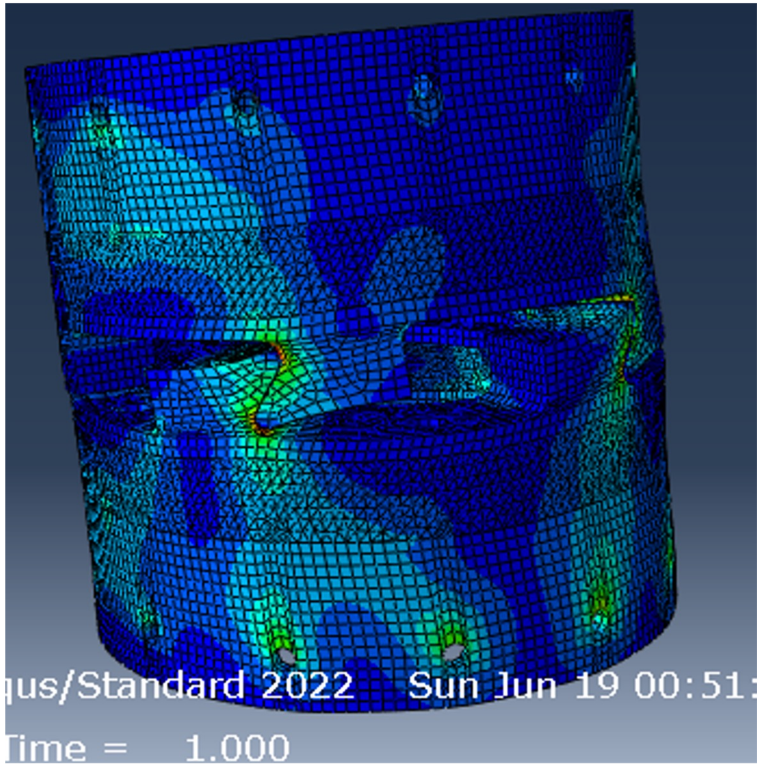
Pin-locking Mechanism
- *Zero-power robust connection requirement*

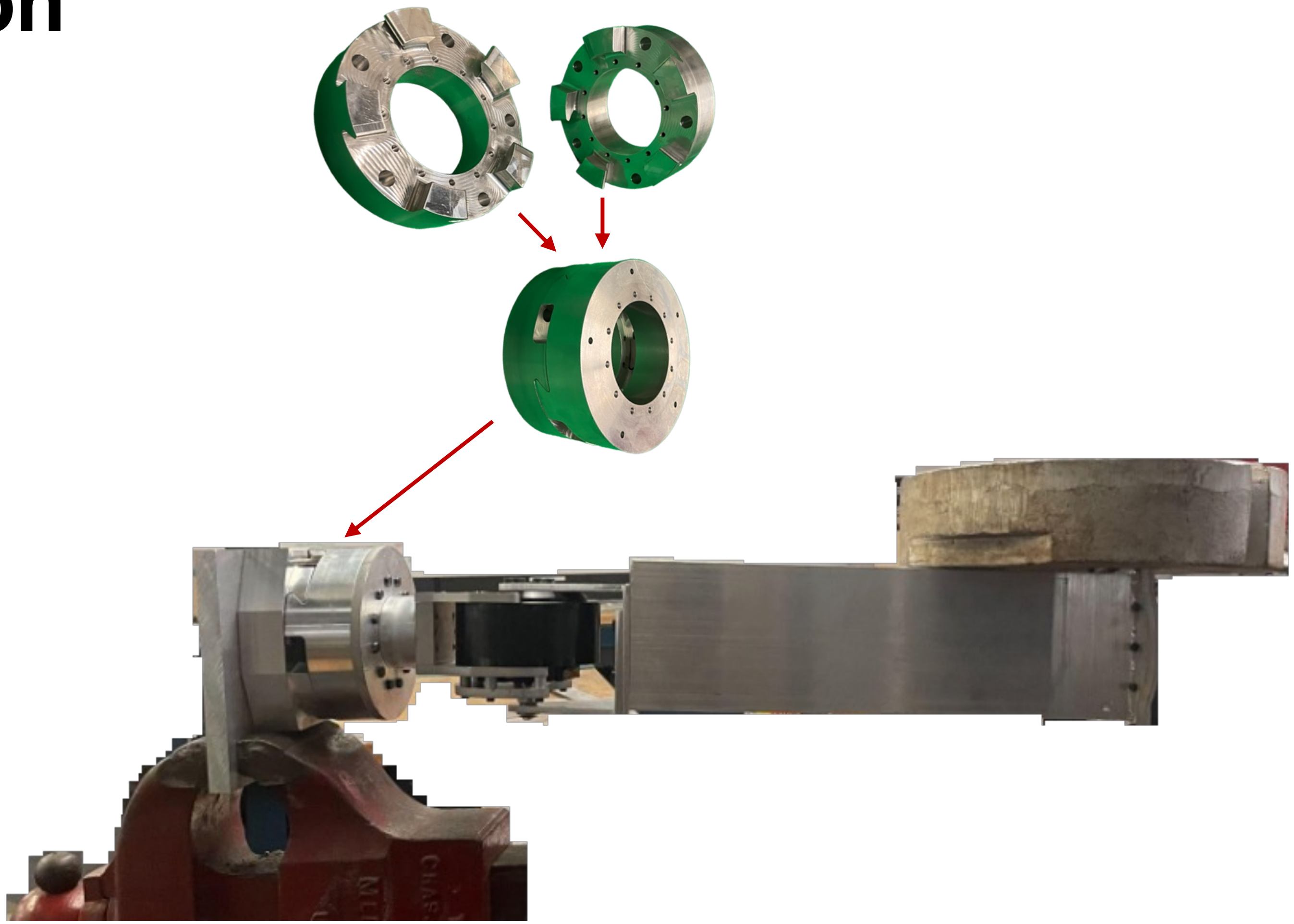
Five-Jaw design
- *Androgynous requirement*



Suspension-desk design
- *Species module space requirement*

UIB Structure Verification

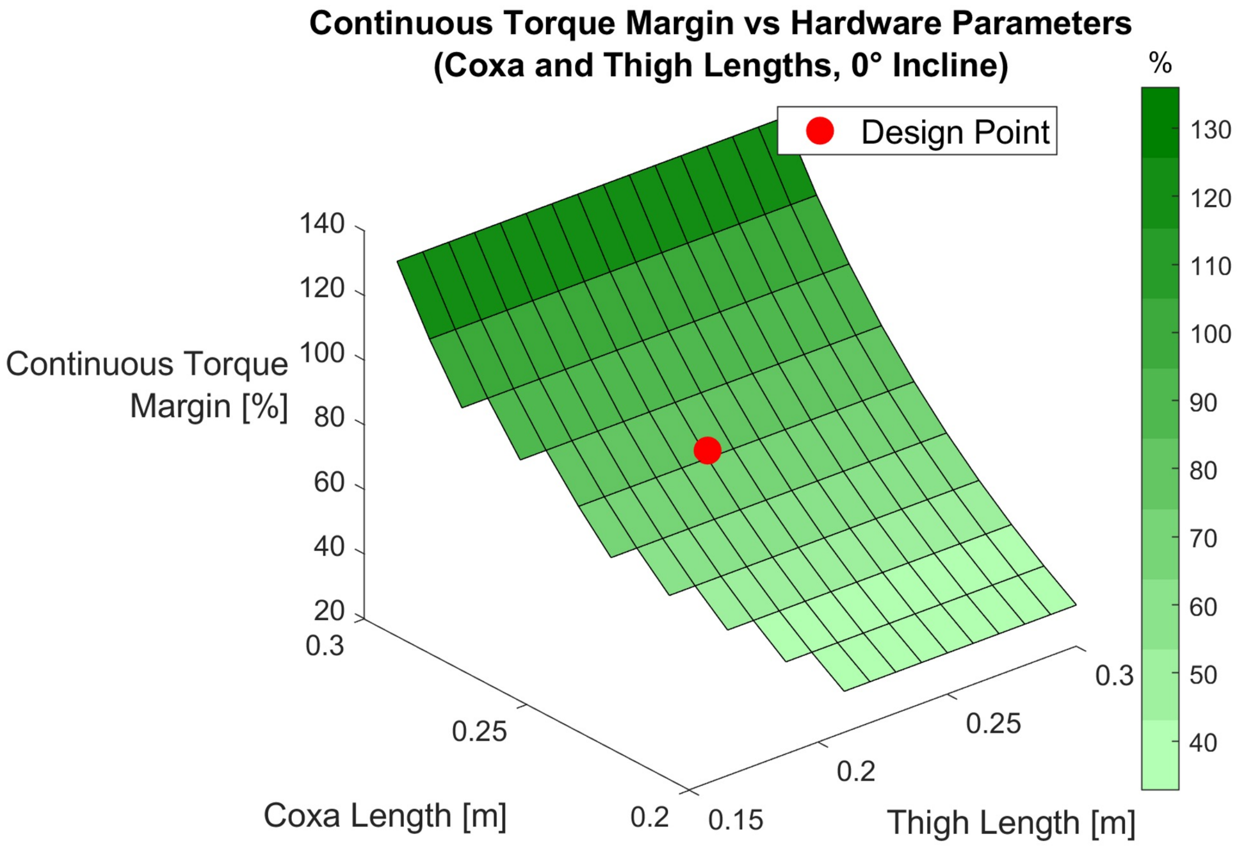


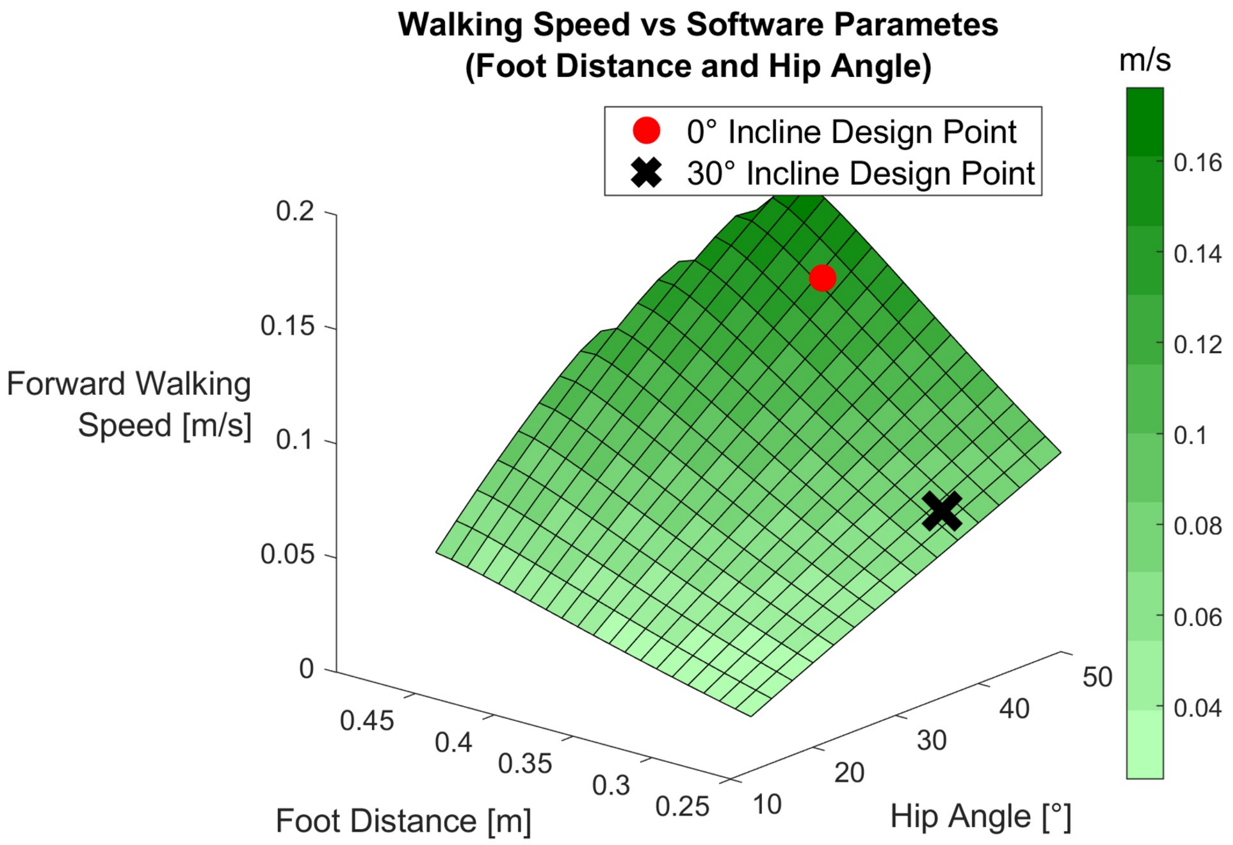


Abaqus CAE FEA Analysis
- Safety factor ~1.5

Experimental Structure Test
- Repeated loading test

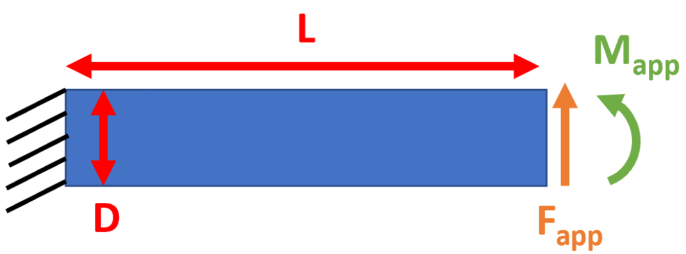
Worm Articulation: Limb Length Selection



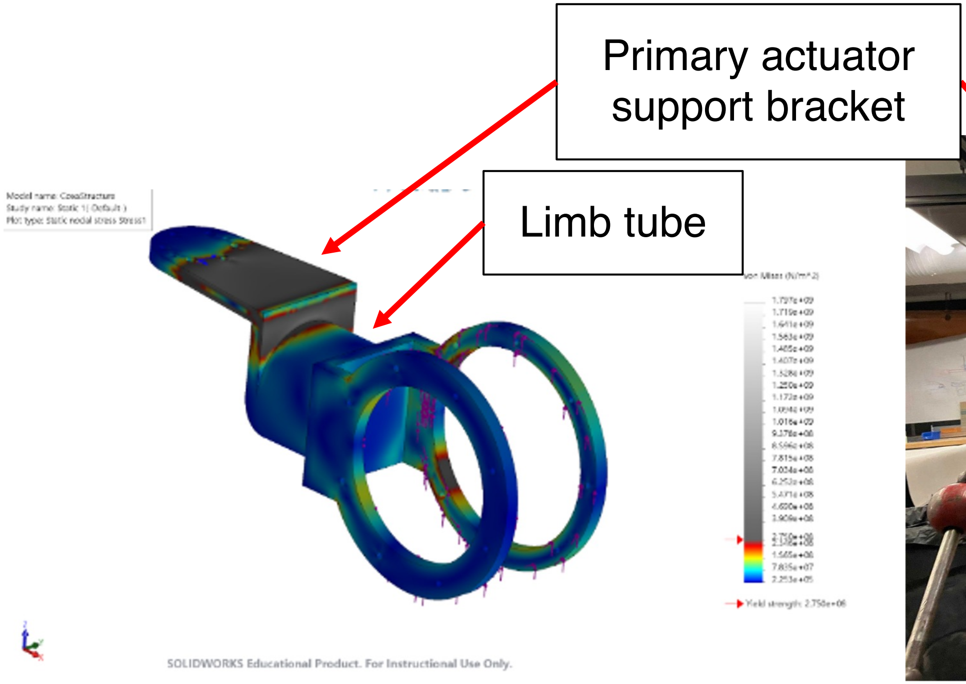


Limb lengths selected to tradeoff actuator continuous torque margin and walking speed.

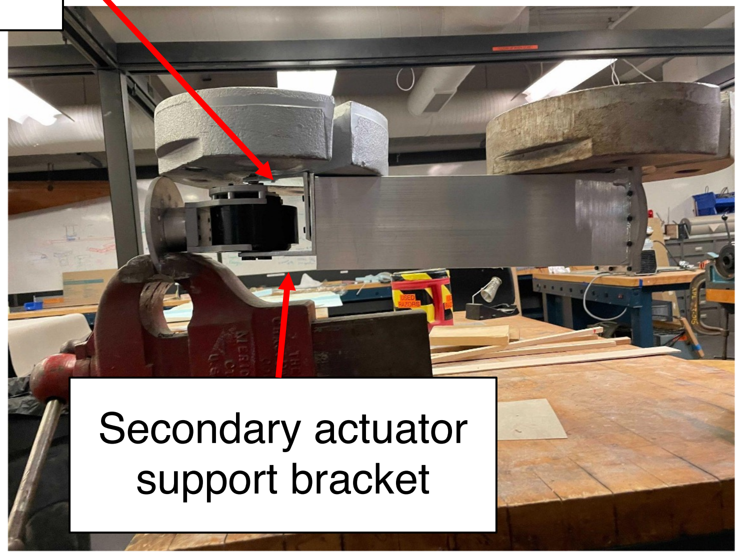
Worm Articulation: Detailed Design



Limb beam model



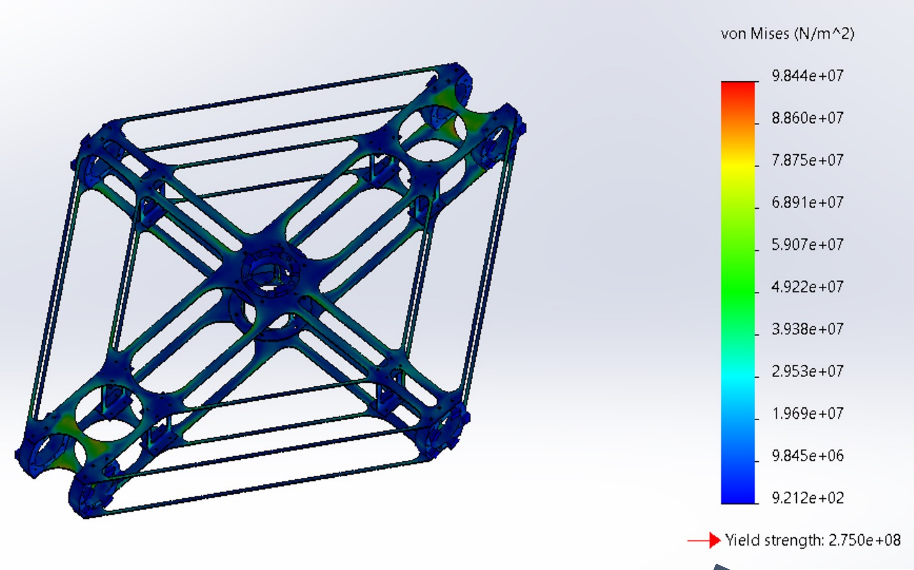
Finite Element Analysis (FEA) of limb design



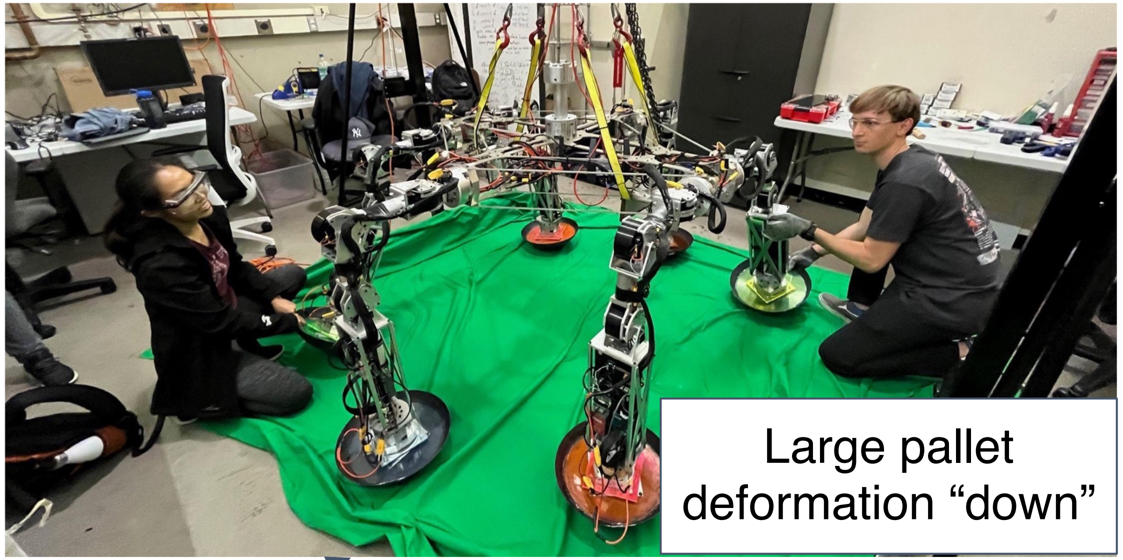
Testing the final actuator interface

Pallet Mechanical Tests and Results

SolidWorks FEA of Pallet Structure

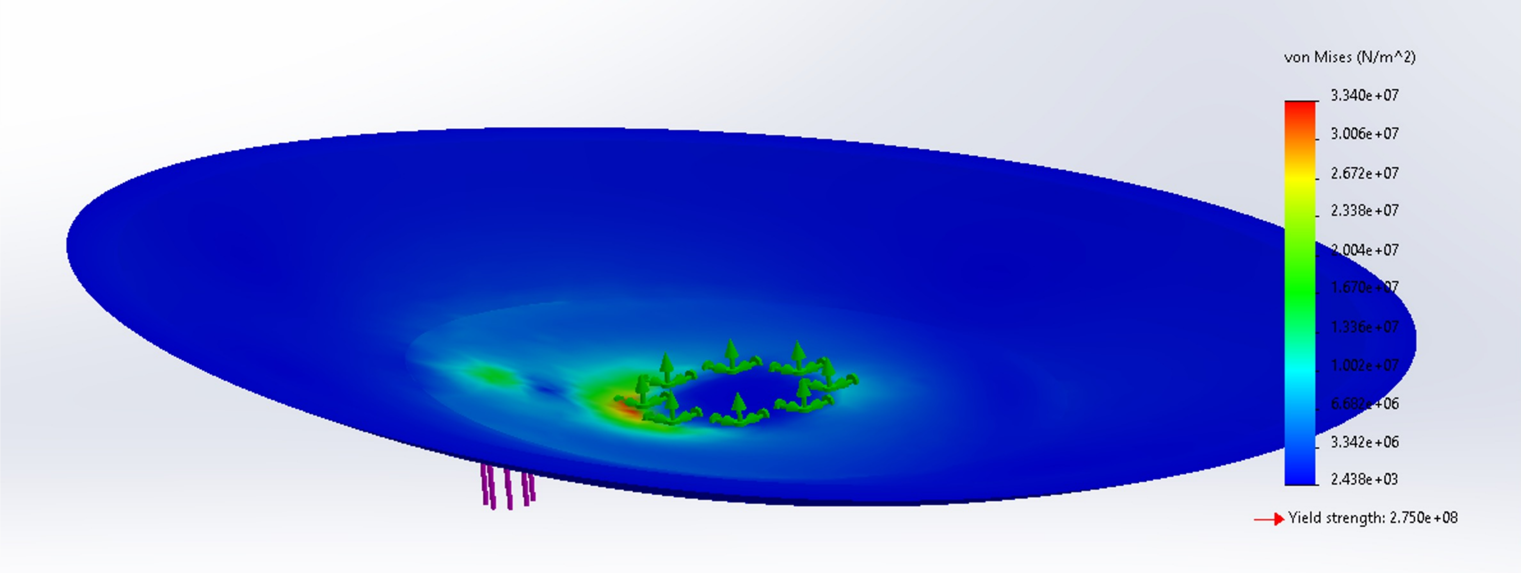


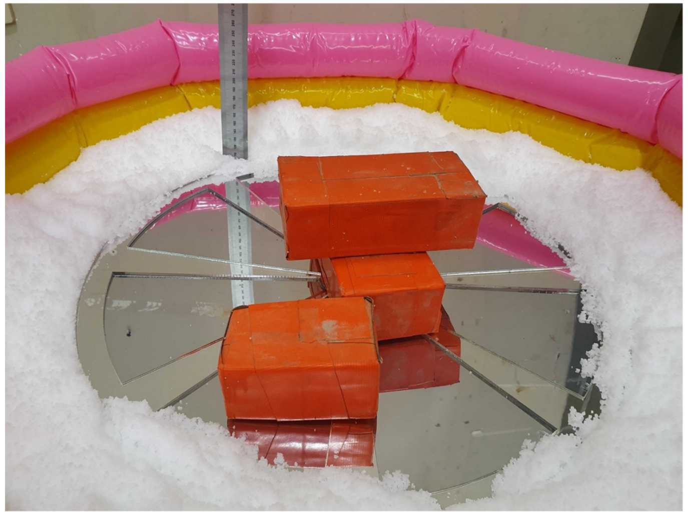
WORMS-1 robot supporting its own weight with 4 unpowered legs



Pallet Element	Max Stress on Element, N/m2		Element Material	Element Material Yield Strength, N/m2	Min Safety Coefficient
	Type 1 Load	Type 3 Load	(aluminum alloy type)		
plate	6.00E+07	9.74E+07	7075-T6	5.03E+08	5.16
neck UIB	1.31E+07	8.44E+07	6061-T6	2.75E+08	3.26
leg UIB	3.25E+07	8.05E+07	6061-T6	2.75E+08	3.42
mid-support	1.64E+07	7.35E+07	6061-T6	2.75E+08	3.74

Shoe Tests and Results

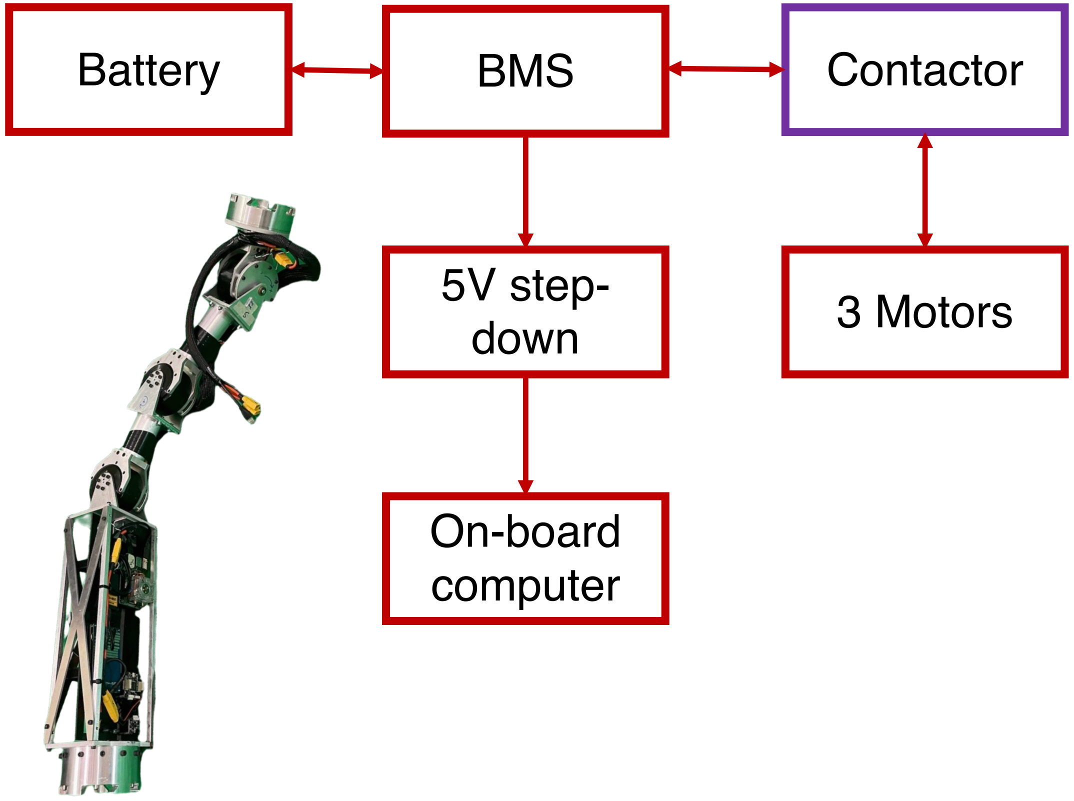




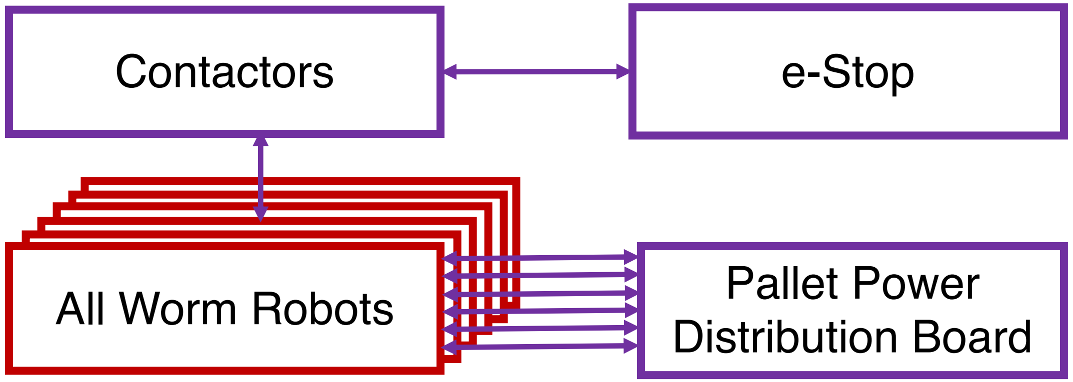
Requirement	Test Conducted	Result
No material yielding during operation	FEA and load test	Pass
Shoe does not sink all the way in high-porosity surface	Shoe prototypes loaded in fake snow	Pass

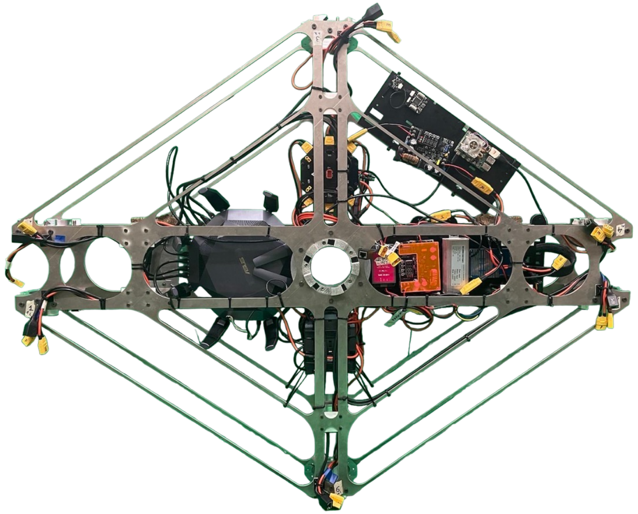
Power distribution: power sharing & e-Stop for test support

Worm Main Power Bus

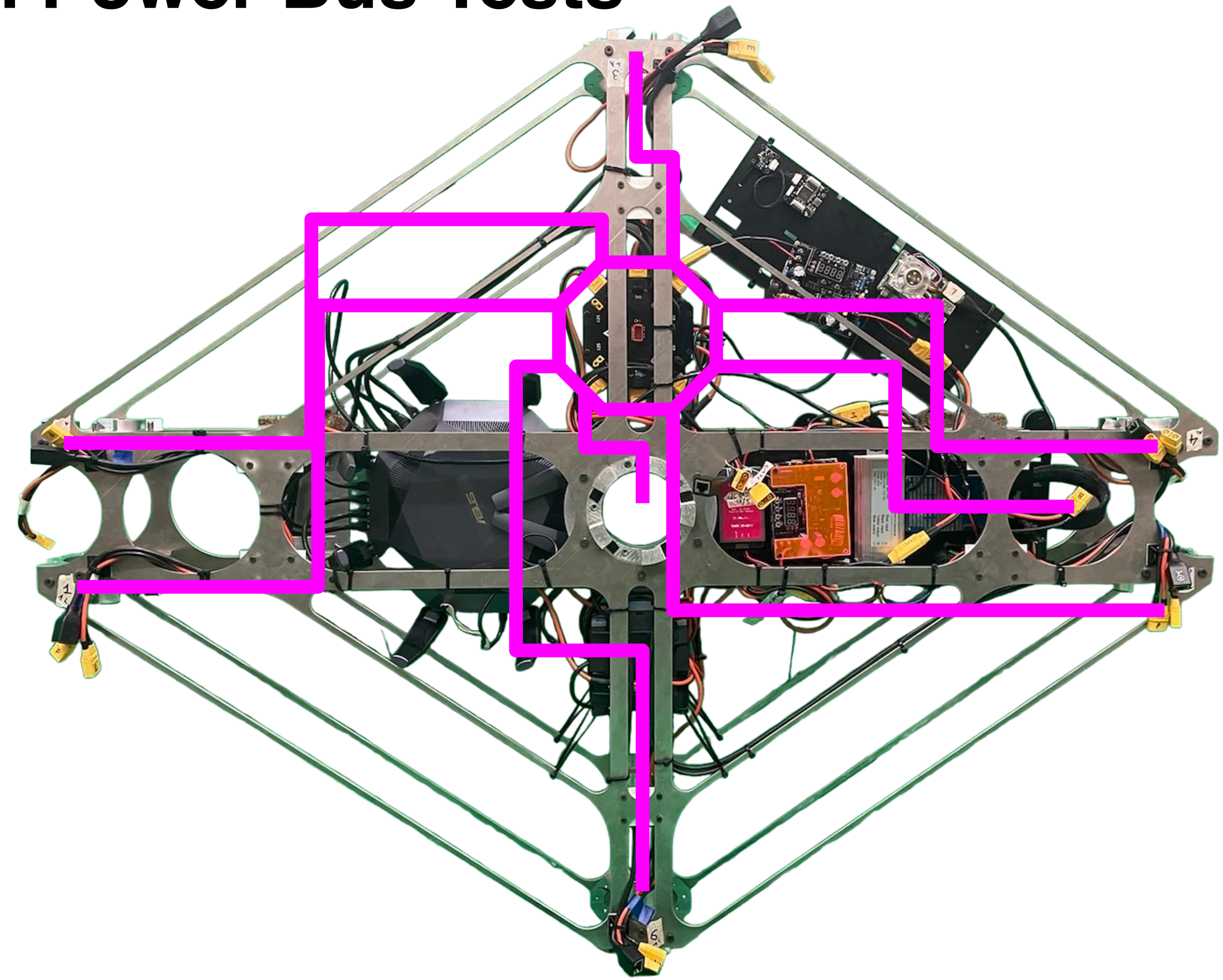


Pallet Main Power Bus

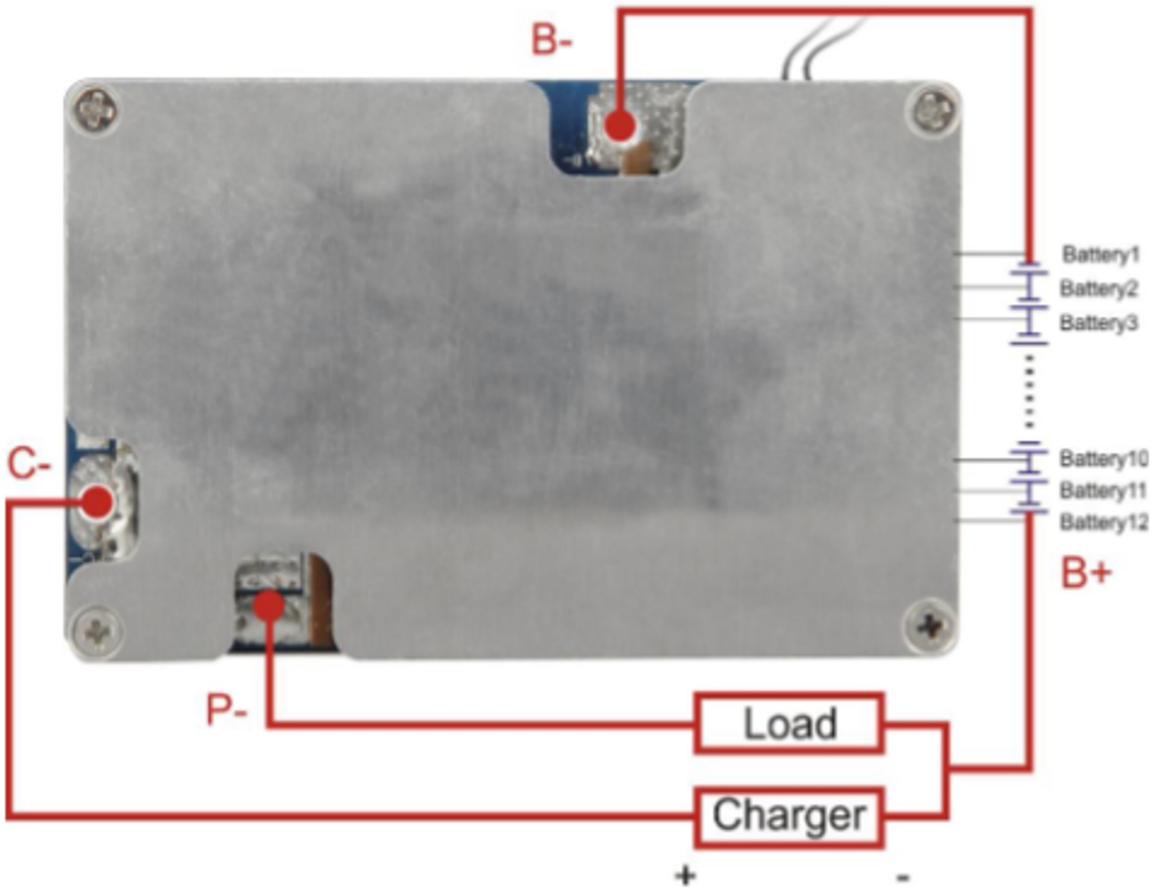




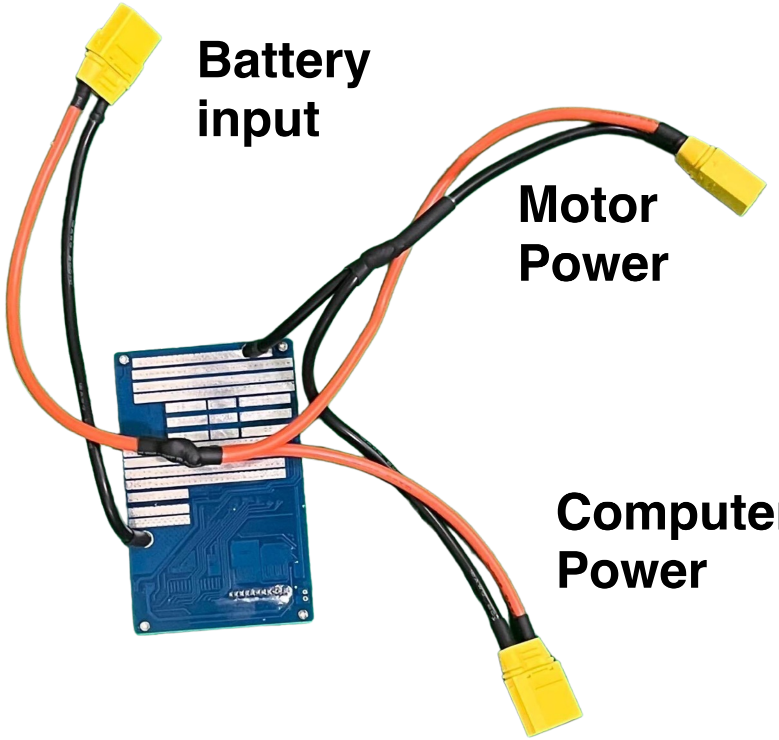
Pallet Main Power Bus Tests



Battery Management System (BMS) Selection and Tests



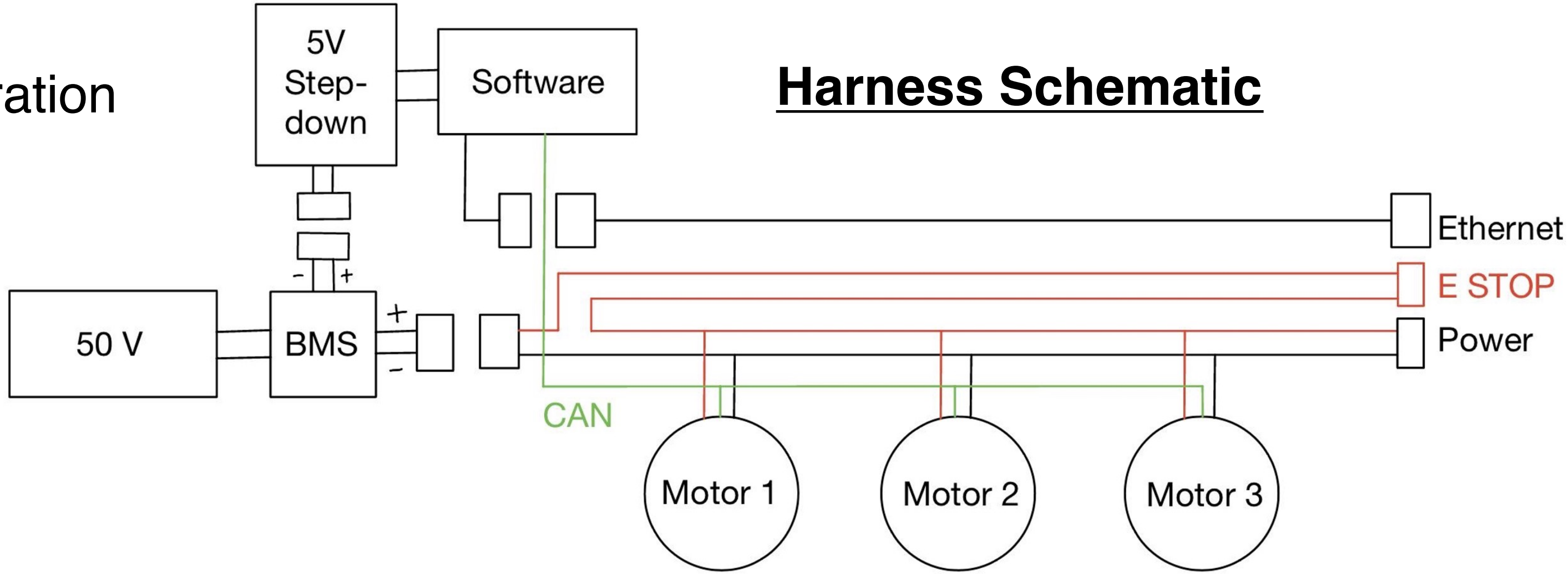
Finalized BMS from Litech
Tests were done with the battery.



Wiring for BMS
Done for all BMSs (7 + spares)

Harness Design and Testing

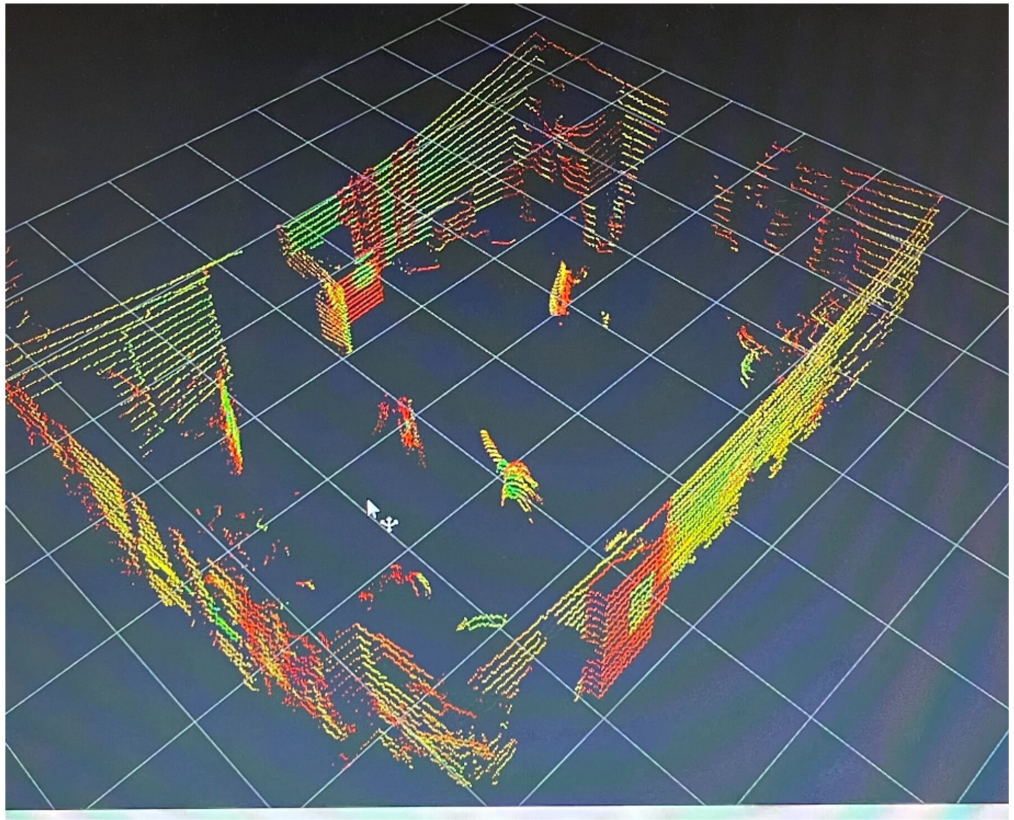
- Harness functions
    - Power and data to 3 motors
    - Power and data between Worms
    - e-Stop capability
- Optimized to safely enable full range of motion
- Extensively tested before integration



Species Module Proof of Concept

Completed “Mapper” Species Module

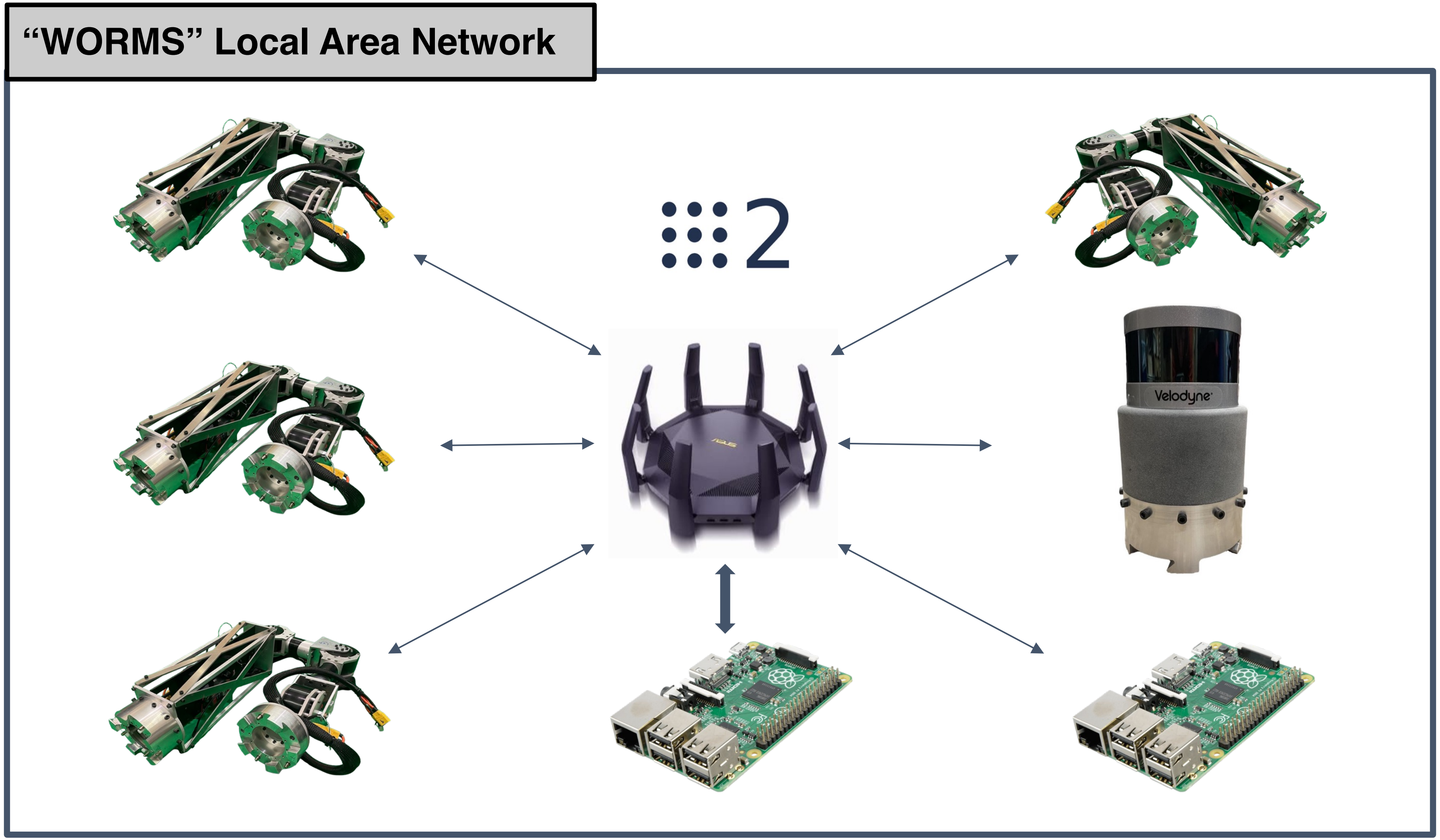
Mapper Interior electronics



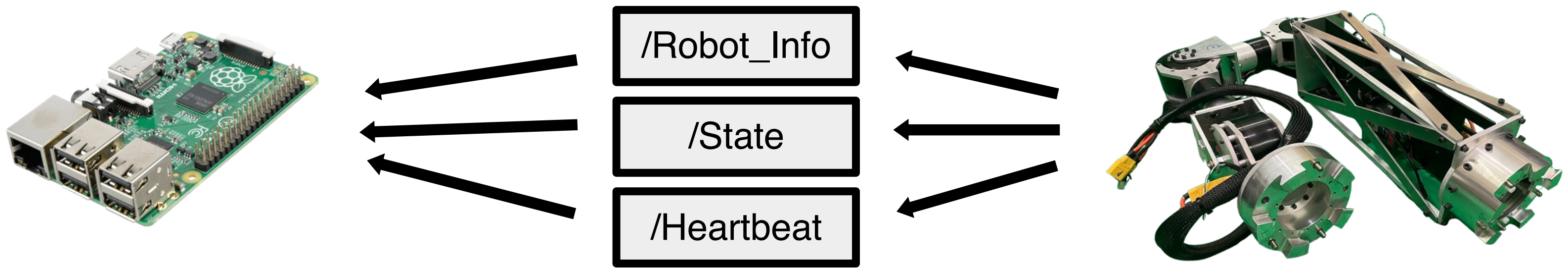
Mapper LiDAR point cloud of MIT Space Resources lab

The Mapper Species Module shares point clouds over the ROS 2 network enabling object detection and SLAM navigation.

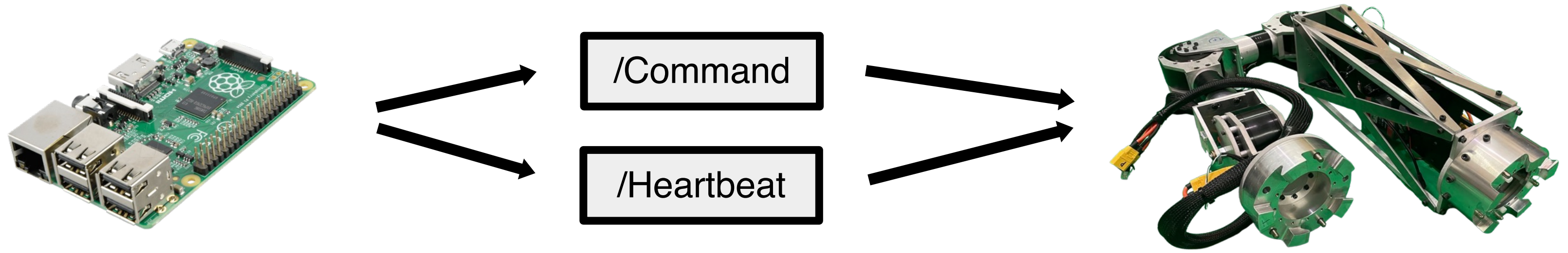
Multi-Agent Communication / Architecture



Communication Framework

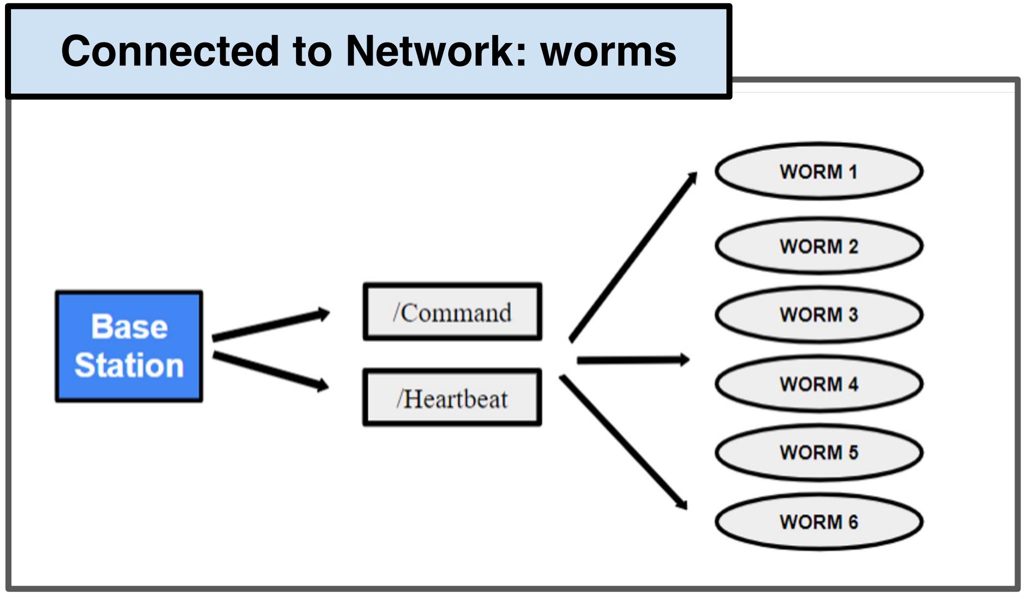


Worm Data Transmission to Base Station



Base Station Data Transmission to Worm

Command Creation and Scheduling



Command = [W_1, W_2, W_3, W_4, W_5, W_6]

#	Name	Notes
0	Set zero position	zeroes the motors
1	Hold position at 0	does not move. Ensures the motors are constantly at 0
2	setup forward	*NO LONGER USED, (setup worm for propulsion phase starting from 0)
3	forward phase	Moves worm from back position to front position (shall be done 2 at a time)
4	propulsion phase	Only done by 1, 2, 4, 5
5	lift leg	Lifts leg from 45 to 90. Hip must be at 0
6	lower leg	Lowers leg from 90 to 45. Hip must be at 0
7	Standby	Does nothing. Used to wait for next command and avoid repetition
8	enable motors	
9	disable motors	
10	45deg	Lifts leg from 0 to 90 degrees. Hip must be at 0
12	setup forward 2	setup worm for propulsion phase starting from 90 degrees. Hip starts at 0

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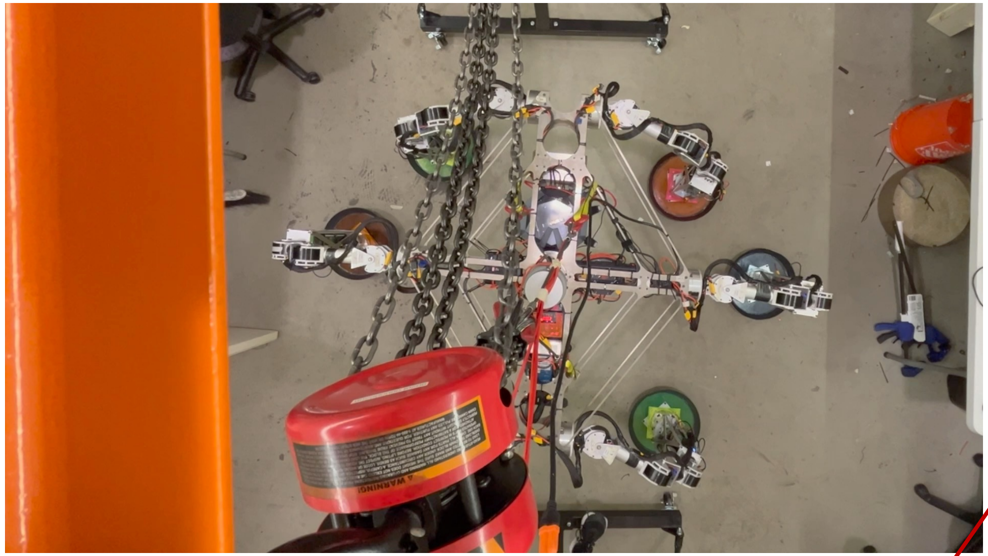
Controlling Worm behavior using command strings

[4,4,4,4,4,4] commands all six Worms to execute propulsion phase move ("4")

W_1	W_2	W_3	W_4	W_5	W_6
8	8	8	8	8	8
0	0	0	0	0	0
2	2	2	2	2	2
4	4	4	4	4	4
3	7	7	3	7	7
7	3	7	7	3	7
7	7	3	7	7	3
4	4	4	4	4	4
9	9	9	9	9	9

Walking gait sequence with 6 feet on ground for propulsion phase



[3,7,7,3,7,7] commands Worms 1 and 4 to reposition forward ("3"). Other worms are commanded to stand by ("7").

W_1	W_2	W_3	W_4	W_5	W_6
8	8	8	8	8	8
0	0	0	0	0	0
10	10	10	10	10	10
12	12	7	12	12	7
4	4	7	4	4	7
7	7	6	7	7	6
3	7	7	3	7	7
7	3	7	7	3	7
7	7	5	7	7	5
4	4	7	4	4	7
7	7	6	7	7	6
9	9	9	9	9	9

Walking gait variant with 4 feet on ground for propulsion phase

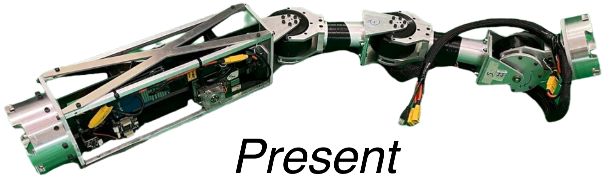
WORMS Path to Flight, Technology Roadmap and Sample Use Cases

Proposed *WORMS-1* tech demonstration mission in 2026

Path to Flight

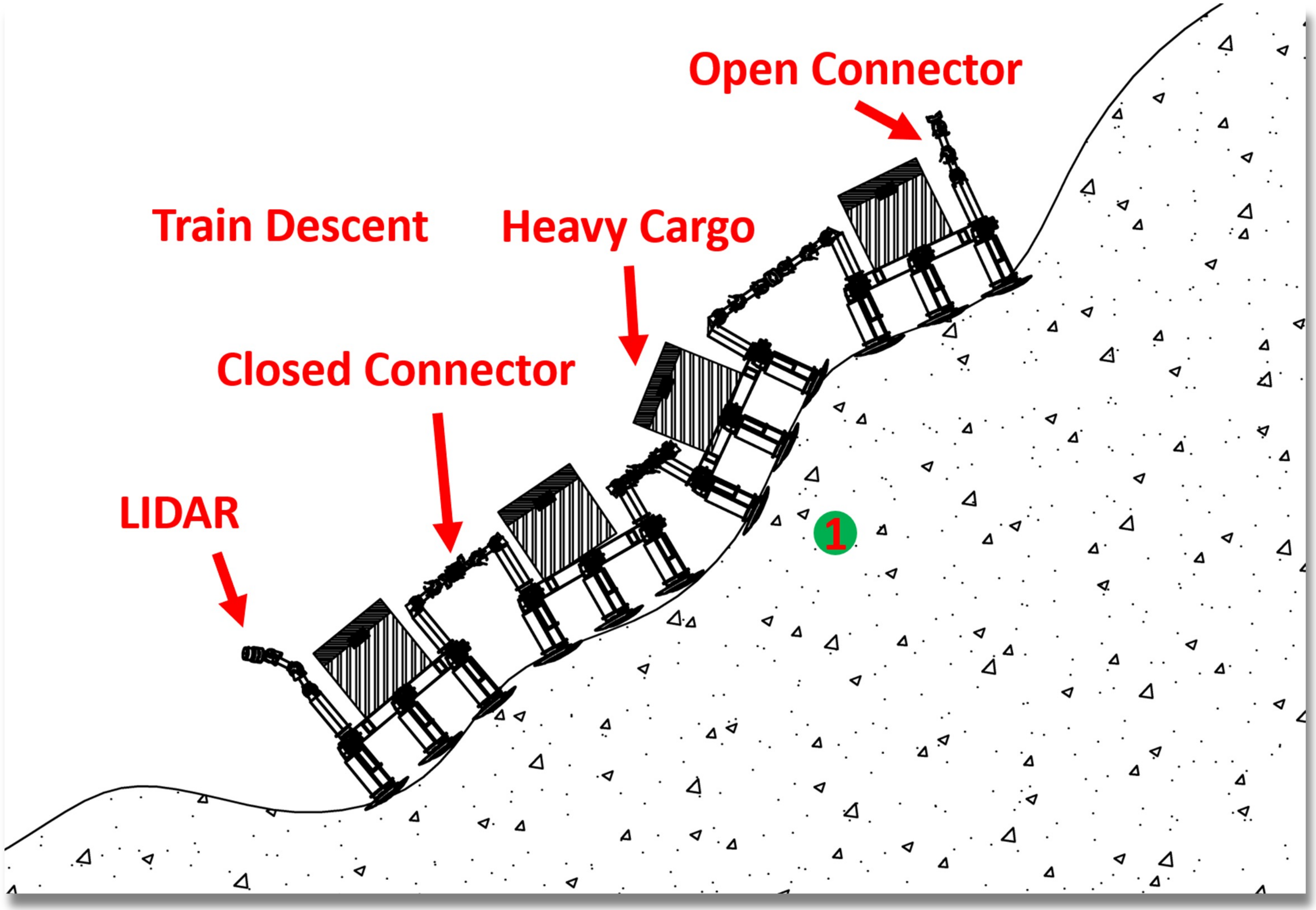
Environmental Change	Required Design / Analysis	Testing Required	Affected Architectural Elements
Gravity	N/A	Weight equivalent walking	Worm, Power
Thermal	Add thermal management system	Thermal cycling, thermal vacuum	All
Vacuum	N/A	Thermal vacuum	Species Module, Power
Radiation	Select rad hardened electronics	Radiation effects testing or by similarity	Power, Software
Dust	Seal actuators, structure	Sand and dust test (Swamp Works)	UIB, Worm, Accessories, Species Module
Launch	Modal analysis	Shock, vibe, acoustic	All

Technology roadmap: three generations of Worms

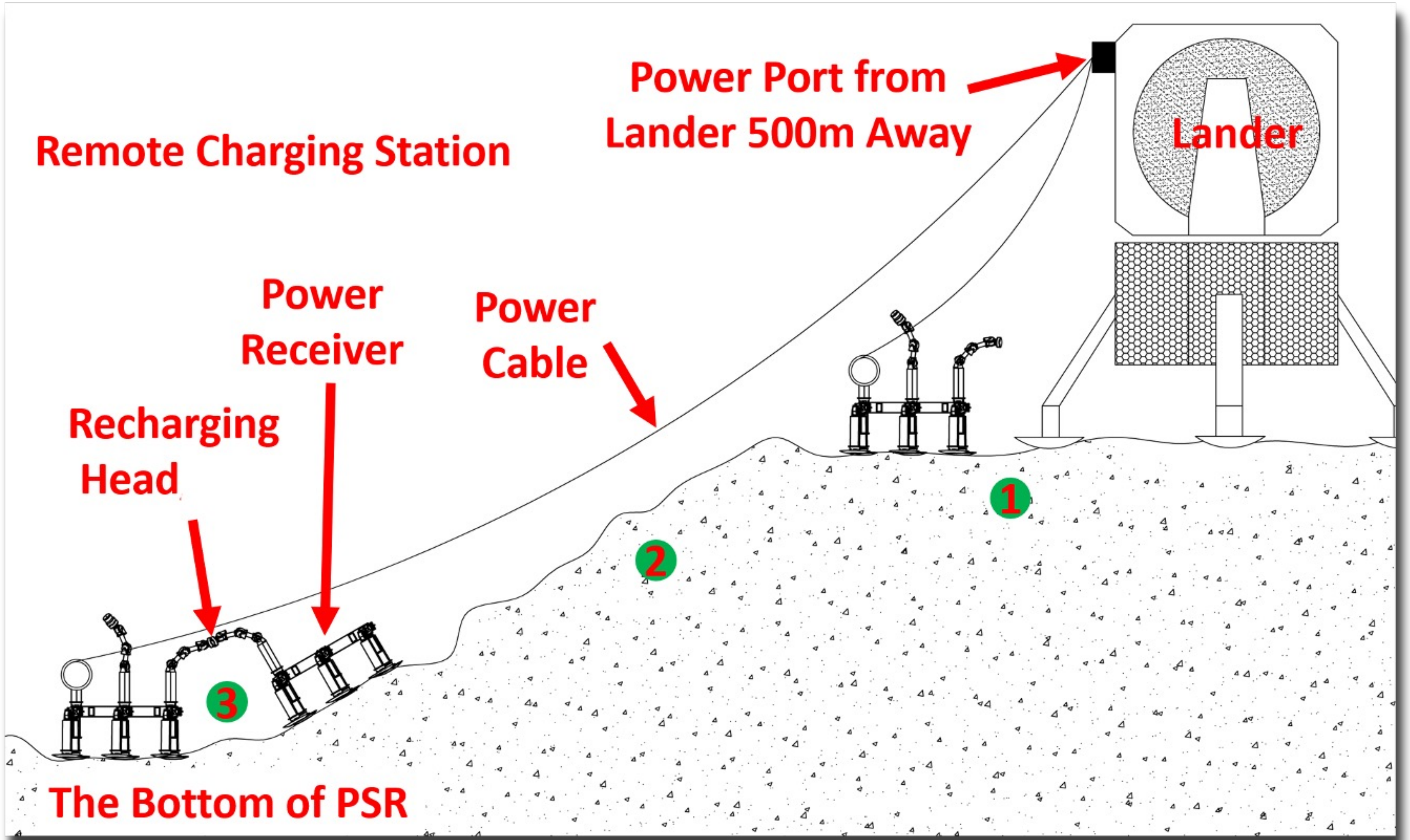


	Present Gen 1	*2024* Gen 2	*2026* Gen 3
Single Worm Mass	10 kg	20 kg	60 kg
Worm Length	~1 m	~1 m	~1.5 m
Hexapod Payload Capacity	**~400 kg**	**~900 kg**	**~1.9 tons**
Universal Interface Block	Androgynous, simple spring-loaded locking pins, custom disassembly tool	Gen 1 + can be disconnected in field by gloved, suited astronaut	Androgynous, larger form factor, autonomous connection and disconnection
Power Sharing	0.24 kWh battery per Worm, passive power sharing	0.72 kWh battery per Worm, active power controllers	2.5 kWh battery per Worm, upgraded active power controllers
Walking Gait	Flat level ground, localization	Unstructured, inclined terrain, SLAM	Gen 2 + adapting gait for sinking surface (porous regolith)

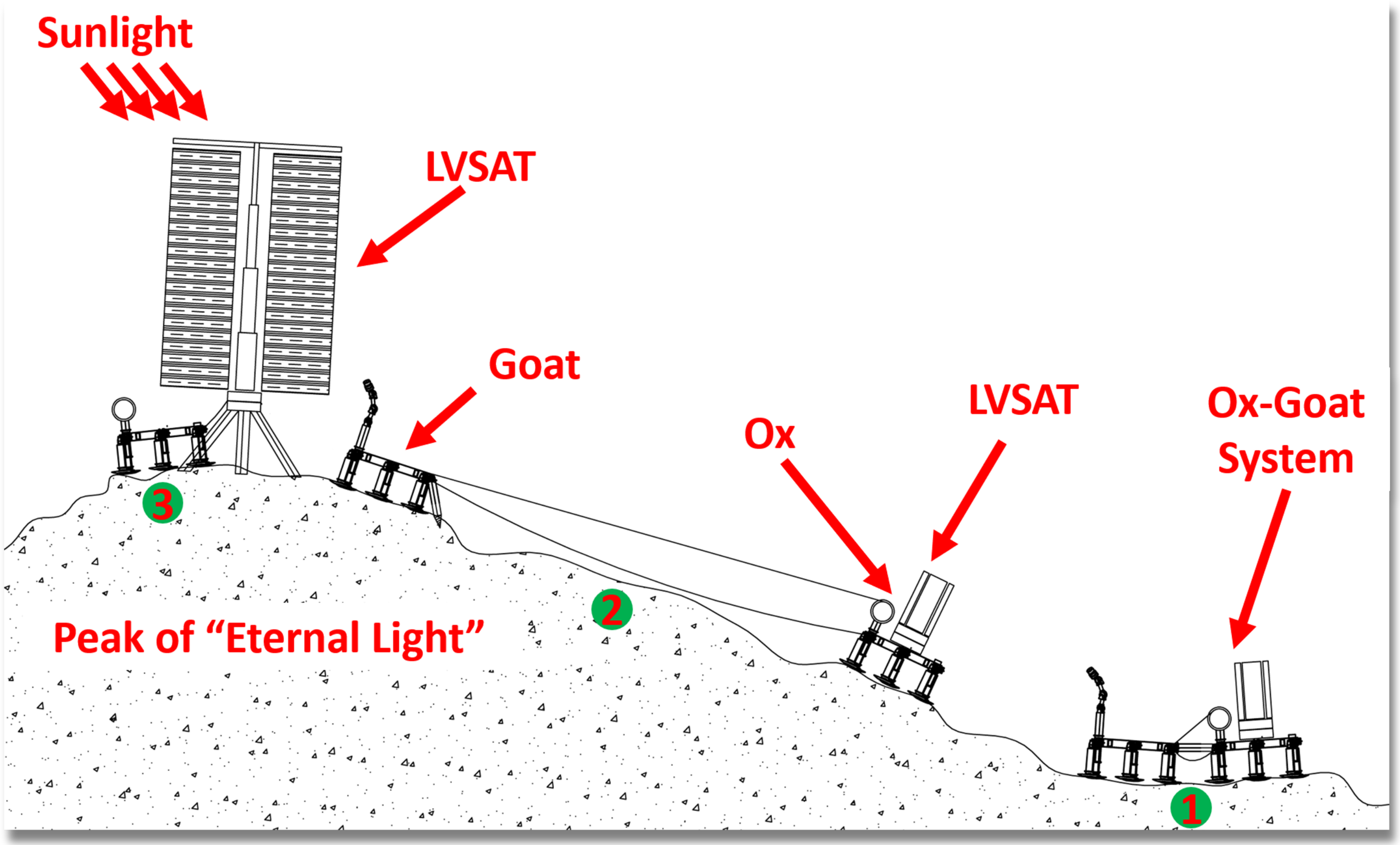
Heavy payloads over steep inclines with a train of Gen1 Worms



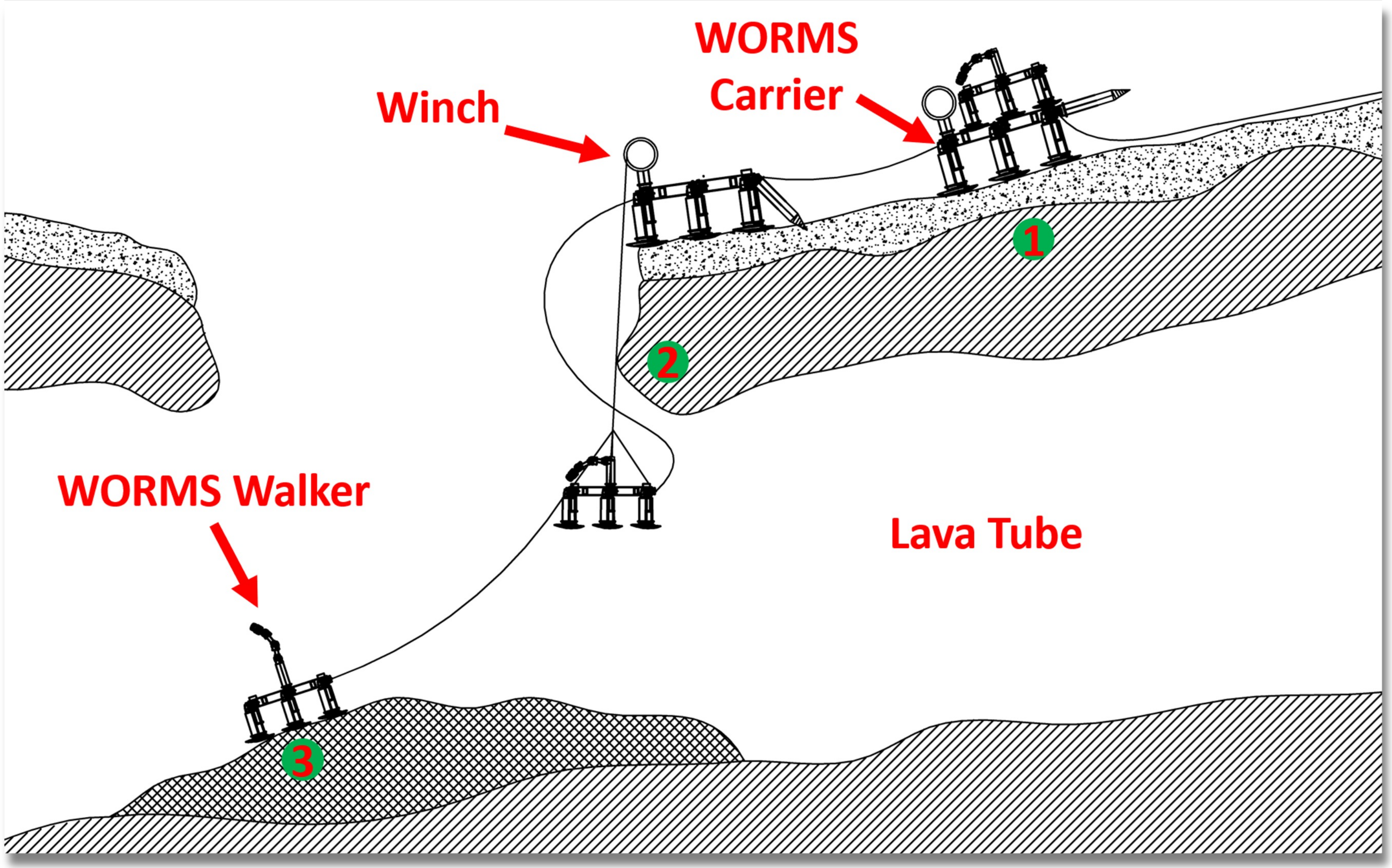
Setting up a charging station inside PSR for other robots/rovers



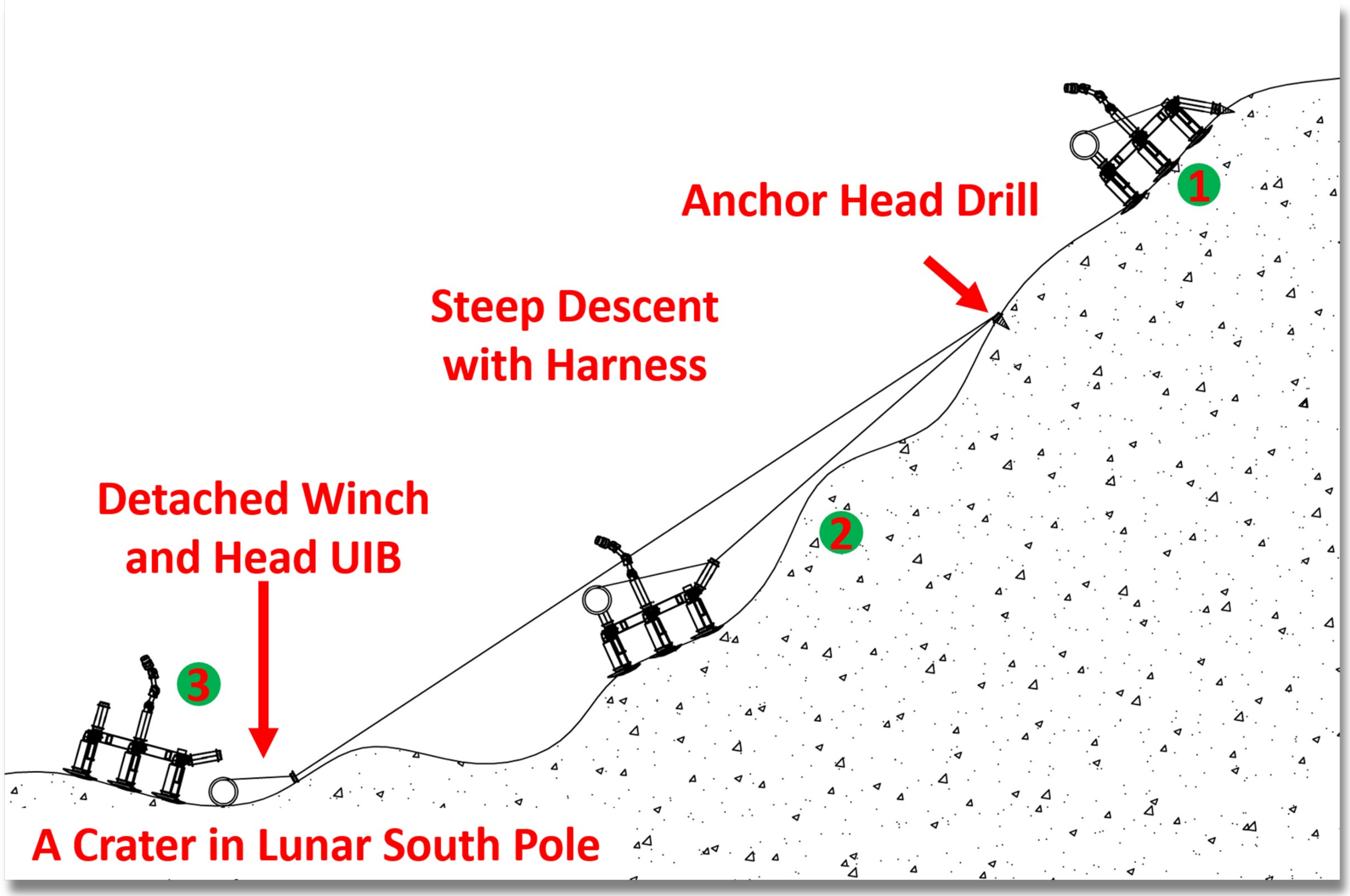
Deploying a heavy solar array to a peak of eternal light



Exploring lava tubes using Gen3 Carrier and Gen2 Walker



Laying and picking up climbing anchors to traverse steep inclines



Other use cases for WORMS robotics

Relocating large surface assets such as habitats

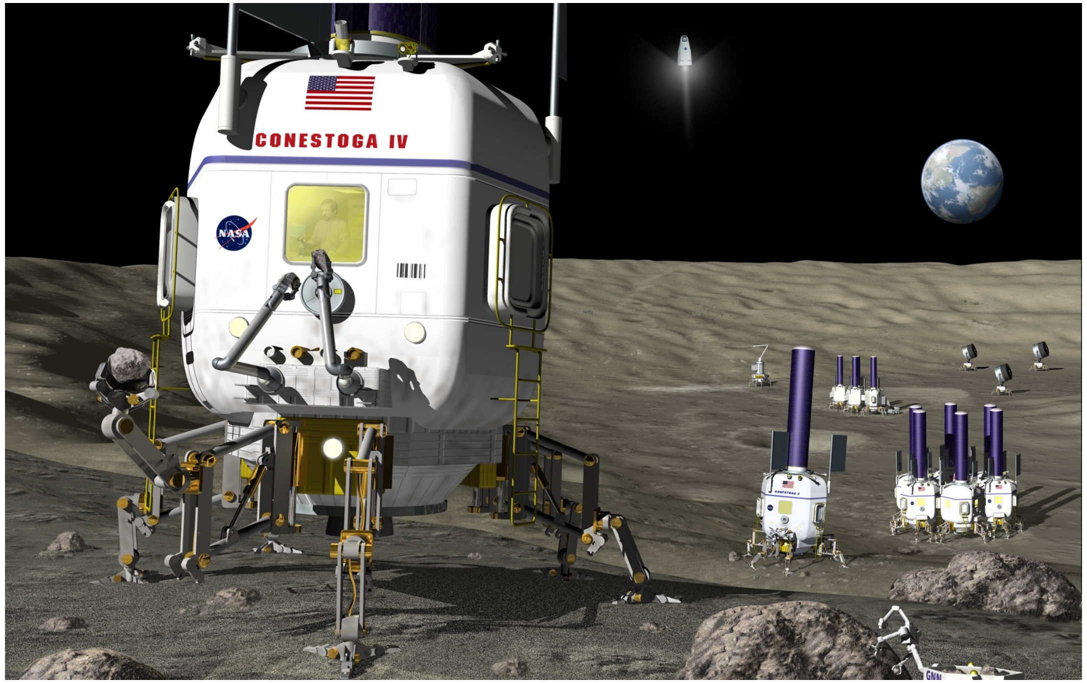


Image credit: NASA

Constructing habitats, roads, landing pads etc.

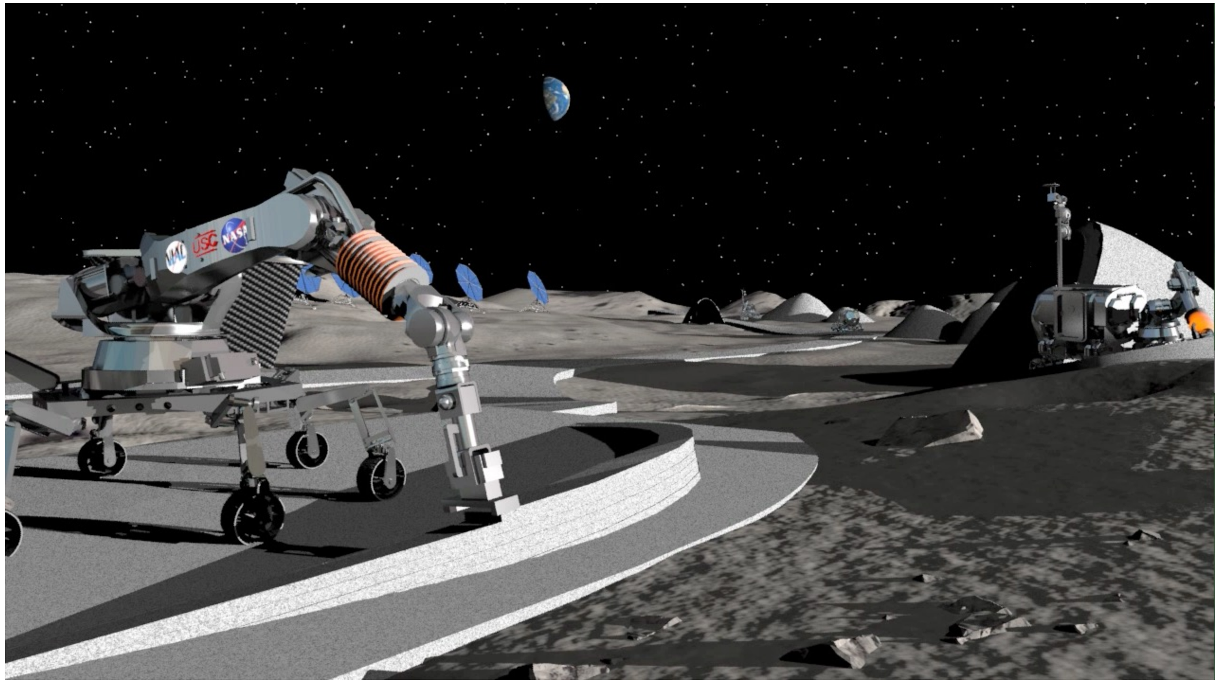
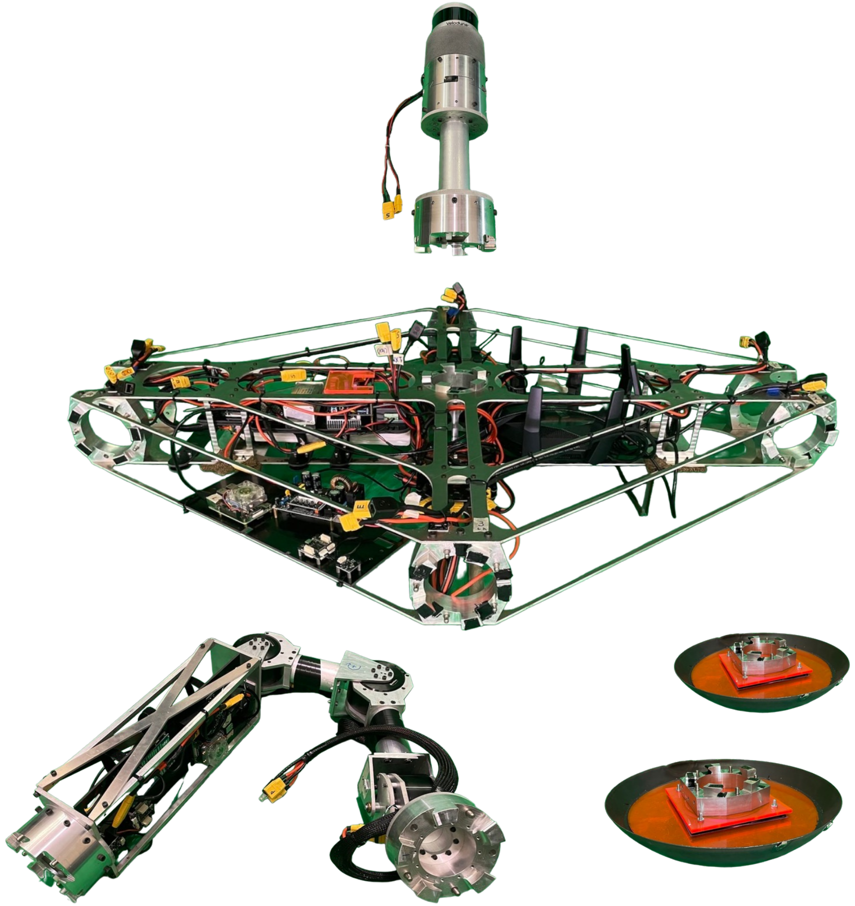


Image credit: USC Center for Rapid Automated Fabrication Technologies (CRAFT)

WORMS virtualizes the robotics hardware layer, turning all new lunar robotics applications into a **100% digital project**.



Acknowledgements

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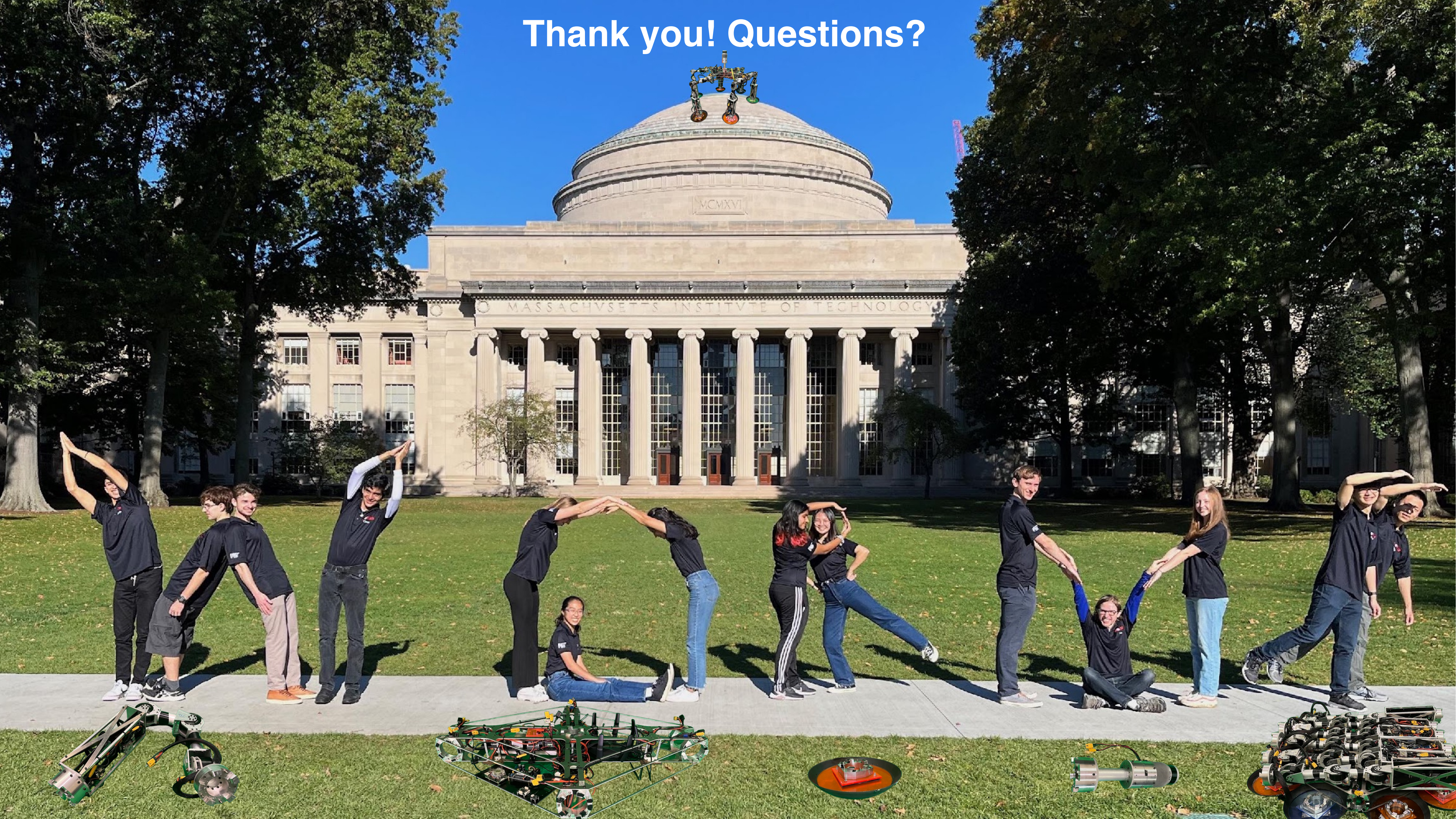
Thank you! Questions?

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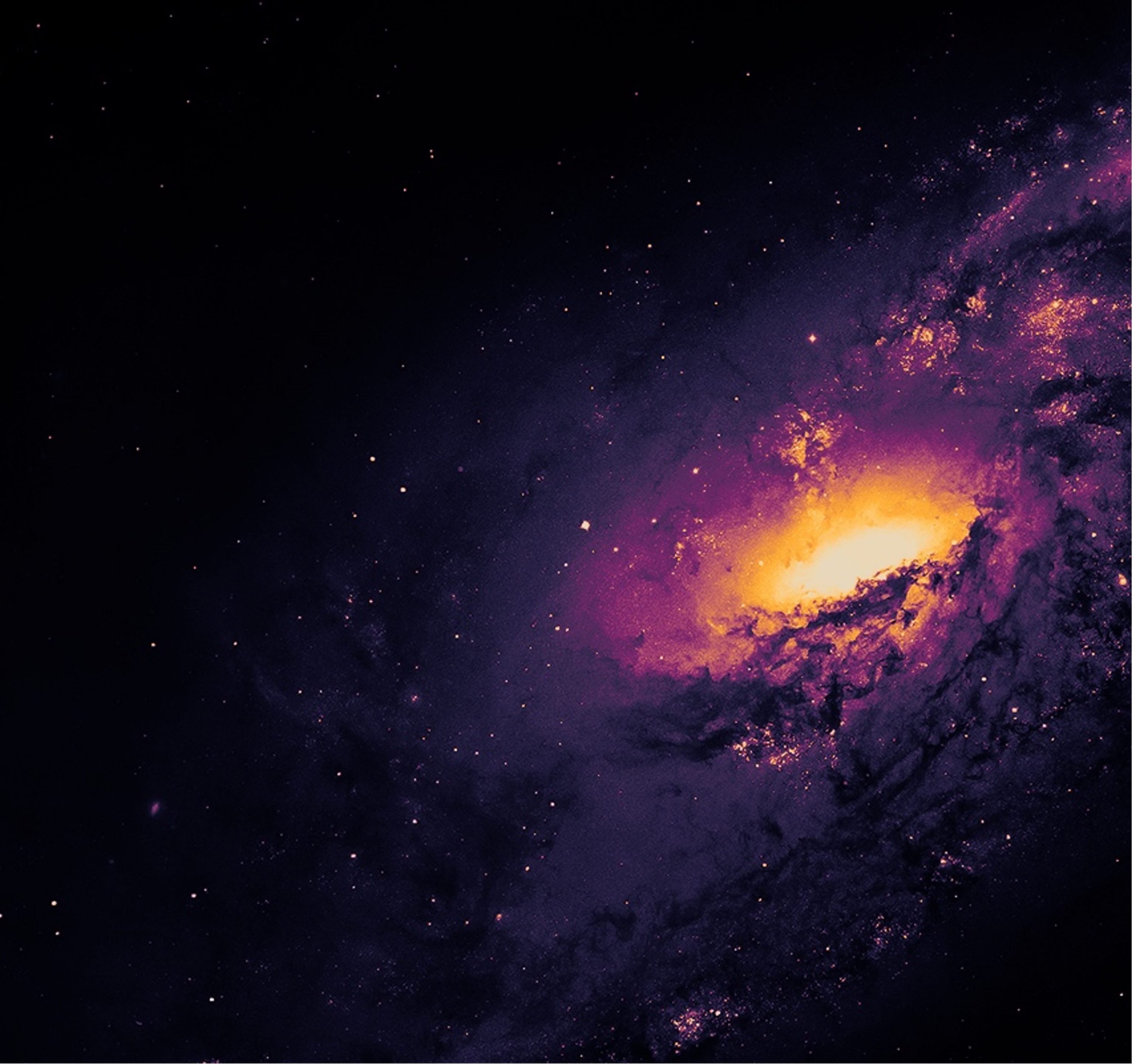

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