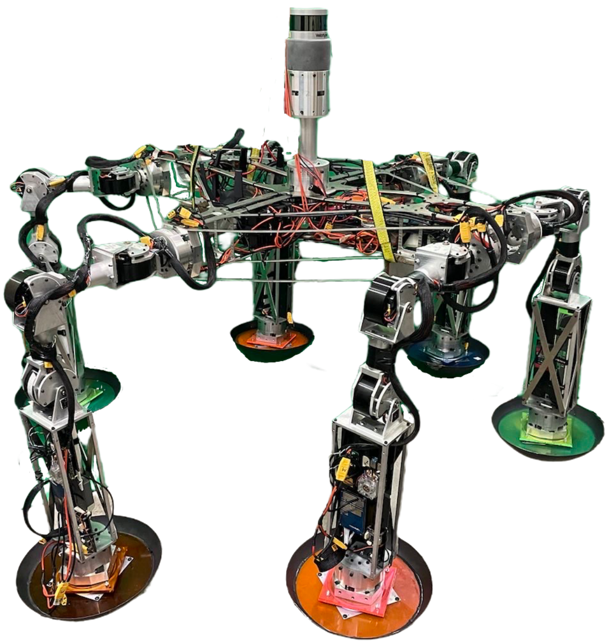
Walking Oligomeric Robotic Mobility System (WORMS) for Extreme Terrain Exploration and Lunar Infrastructure Development

October 24, 2022: Final Report to NASA's 2022 BIG Idea Challenge

Massachusetts Institute of Technology



Team: George Lordos[1,b,+,L], Michael Brown[2,b,*, L], Yang Chen[1,a,+,L], Cesar Meza[3,b,*,L], Jacob Rodriguez[3,b,*,L], Alex Miller[1,b,*,L], Aditya Mehrotra[3,c,*,L], Prajwal Mahesh[3,a,*, L], Cormac O'Neill[1,a,*, L], Aileen Liao[3,a,*,L], Brooke Bensche[3,b,*,L], Sharmi Shah[3,a,*,L], Kir Latyshev[1,b,+,L], Jessica Rutledge[3,b,*], Cynthia Cao[3,b,*,L], Fatema Zaman[3,c,*], Steven Reyes[3,c,+], Tomas Cantu[3,b,+], Diego Rivero[3,c,*], Katherina Sapozhnikov[3,a,*], Anna Mokkapati[3,c,*] Chiara Rissola[3,d,*], Fiona Lin[3,a,*], Paula do Vale Pereira[1,b,+], John Zhang[1,a,*]

Faculty Advisors: Prof. Jeffrey Hoffman[b,*], Prof. Olivier de Weck[b,*], Prof. David Trumper[a,*], Prof. Sangbae Kim[a,*]. External Mentor: Prof. Wendell Chun, University of Denver

Industry Partners: Boston Dynamics, MassRobotics, Robots5

*1: PhD Candidate. 2: MS Candidate. 3: Undergraduate. a: MIT Department of Mechanical Engineering. b: MIT Department of Aeronautics and Astronautics. c: MIT Department of Electrical Engineering and Computer Science. d: Carnegie Mellon University. *: US Citizen. +: International. L: Team / Sub-team / Product lead.*

MIT AEROASTRO MITMECHE MIT EECS

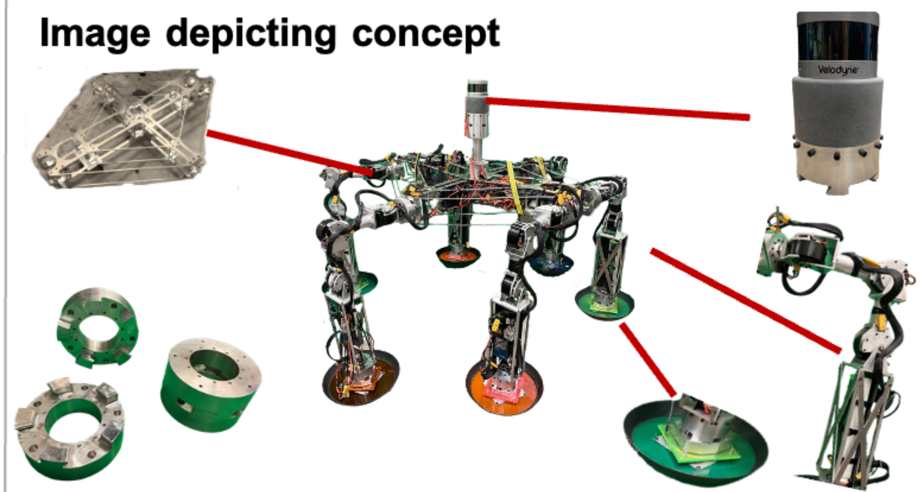
Table of Contents

Walking Oligomeric Robotic Mobility System (WORMS)
Massachusetts Institute of Technology
With Boston Dynamics, MassRobotics and Robots5

Concept Synopsis

- **Worms** are articulating worm-like robots and are fitted with a Universal Interface Block (UIB) at both ends.
- The **UIB** is a mechanical androgynous interface which forms a robust connection between architecture elements.
- **Accessories** are simple structural forms, such as shoes, pallets or spools, and also come with at least one UIB
- **Species Modules** also have at least one UIB, and add functionality to worms such as winching, drilling, mapping.
- Using the above, with **software**, an astronaut can quickly assemble a robot tailored to a particular mission.
- WORMS is a scalable, efficient, versatile, and easily maintainable platform for **reconfigurable lunar robots**.

Image depicting concept



Innovations

- The major innovation is the creation of a platform of reconfigurable robots that could support not just extreme terrain access, but also other mobility / robotics use cases on the Moon.
- The WORMS platform modularizes the hardware layer, making new lunar robotic architectures an essentially **digital project**. New robot configurations and code can be beamed to the Moon or Mars at the speed of light.
- The UIB is the key new technology which enables the entire WORMS platform of reconfigurable robots.
- A new walking gait, the "Magic Carpet", was created from first principles.

Verification Testing Results & Conclusions

- We demonstrated the following:
  - Coordinated walking by a robot made of 6 robots
  - The UIB can form robust connections
  - The six Worms can share their battery power with each other
  - This robot could carry 3X to 4X its mass in payload on the Moon
  - A new hexapod walking gait, "Magic Carpet"

1 Executive Summary and Value Statement

The title of this project -- Walking Oligomeric Robotic Mobility System (WORMS) -- refers to a unique platform architecture for field-reconfigurable robots to support a variety of lunar surface operations. WORMS consists of a set of identical, articulating worm-like robots (Worms), together with a small set of simple Accessories, such as different types of shoes or pallets / chassis, which can be assembled into larger robot configurations tailored to the needs of various extreme terrain access missions. Each Worm or Accessory can optionally be enhanced with added functionality defined by interchangeable Species Modules. These could include a LIDAR unit, an anchoring drill, a winch, an additional battery and many more tools or sensors. The key idea is that all elements of WORMS can be easily reconfigured in the field by non-specialists to accomplish a large variety of mobility missions, including but not limited to extreme terrain access, provided only that the required elements are on hand at Artemis Base Camp and that the software has already been developed for a given configuration.

Since our midterm report, we have built and tested our proof-of-concept WORMS-1 robot and matured it to TRL 4. Our hexapod WORMS-1 robot, shown on the cover and in Fig. 1, consists of a pallet with seven Universal Interface Block (UIB) attachment points, fitted with six Worms which serve as legs, and a Mapper 'species module' equipped with doppler LIDAR. The leg Worms are fitted with Apollo-like footpad 'shoes', also attached via our UIB interface, while the pallet power bus supports power sharing from and to all connected Worms. As designed and built, this proof-of-concept robot weighs ~120kg and a similar flight version could carry a payload of ~400kg on the Moon. Through a series of subsystem tests and 17 integrated tests, we have demonstrated a basic autonomous walking capability on level ground. We have also shown that our universal interface block (UIB) is functional and robust, enabling our vision of field assembly of different robots. Further, we have tested and demonstrated the power-sharing capability between Worms. We also demonstrated the functionality of prototypes for our first accessories – the shoe and pallet – as well as our first species module, the Mapper, which uses a LIDAR unit to map the surroundings of the robot. Overall, we matured the WORMS robotic platform and each of its key elements starting from TRL 1 in Nov 2021, reaching TRL 4 in Oct 2022.

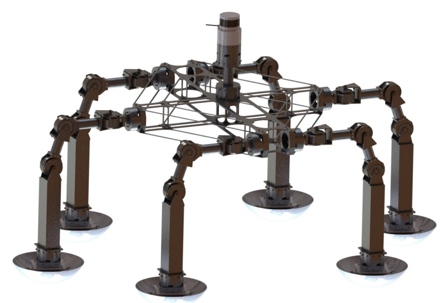


Figure 1 Render of our as-built proof of concept

A flight article derived from our prototype would be delivered by a Commercial Lunar Payload Services (CLPS) lander near a permanently shadowed region (PSR) in the lunar polar region. WORMS-1 unspools cable as it walks at 0.1 – 0.14 m/s over highly porous and inclined terrain while also creating a LIDAR point-cloud map of the area. At the end of its journey, WORMS-1 becomes a recharging and data relay station for the other robots and rovers exploring this PSR.

We realized early on that NASA and its partners are likely to have *substantial*, *expanding*, *evolving* and *diverse* needs for robotic support in the years to come, including but not limited to extreme terrain mobility, and so we decided that our solution should aim to deliver both present and *future* value. Therefore, beyond the immediate recharging and data relay station application proposed for WORMS-1, we have designed our platform architecture to feed forward into NASA's Plan for Sustained Lunar Exploration and Development and into plans by commercial and international actors for a permanent presence near the lunar south pole [1]. For example, a third-generation hexapod configuration, with a winch-and-cable species module and a payload capacity of 1.9 tons, could lower a 200kg Gen2 WORMS hexapod carrying a 600kg payload into a lava tube to explore, collect samples, or construct a habitat. WORMS' long-term impact on NASA's lunar strategy lies in its potential to support various extreme terrain mobility missions throughout Artemis and beyond. New modular robots can be reconfigured and redeployed in the field, when the necessary software becomes available. New accessories, new worm species with different sizes and new functionalities can be developed as the need arises, such as supporting extreme terrain missions and infrastructure development that requires heavy-duty surface mobility. Mass production of worm units will lead to lower costs and improved maintenance logistics, while higher levels of system reliability can be achieved by adding redundant worms to any given configuration, or by replacing worms in the field and continuing a mission. Finally, hardware obsolescence will be very limited as WORMS from no-longer-needed configurations can be reused in new robots. Our strategy is that WORMS should become a mass-producible, reconfigurable, reusable and scalable robotic platform, so that it can be potentially of value to most future operational scenarios that could be envisaged.

2 Problem Statement and Background

In our exploration of the design space, which ultimately led to conceiving, designing, building and testing our field-reconfigurable WORMS robotics platform for lunar surface operations, we soon realized that in the coming decades, many different robots could end up being developed and used for many different specialized surface operations. For instance, NASA and its international and commercial partners will need to power their fixed and mobile systems; explore, traverse or operate in extreme terrain; deploy and maintain fixed and mobile systems of various sizes and levels of complexity, and so forth. In the absence of a single robotics platform that could meet all these needs, there is a risk of piecemeal, incompatible investments in lunar surface robotics and, over time, a serious risk of accumulation of substantial technical debt.

Hence, back in November of 2021, we reframed the problem: instead of searching for the optimal robotic architecture that could support our chosen application of powering other robots operating inside a PSR, we set about conceiving of a robotics platform that could support a variety of different missions, including our chosen use case.

2.1 A Stakeholder Value Network for the WORMS project

The first steps in our search for a versatile extreme terrain mobility design were to perform background research on the environmental conditions near the lunar South pole and to map out the value exchanges between key stakeholders including NASA, its commercial and international partners, as shown in Fig. 2, so as to understand high-level needs that could be served by specialized non-wheeled robots.

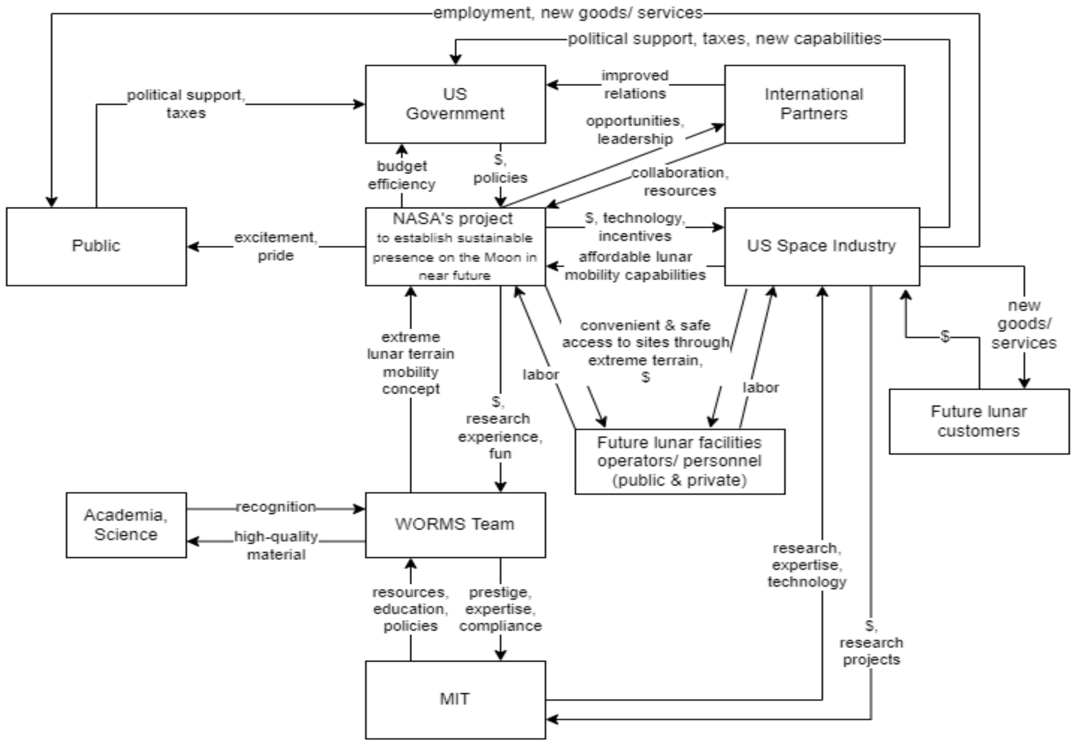


Figure 2 A Stakeholder Value Network for the WORMS project [2]

Our stakeholder analysis started by mapping the NASA, international and commercial stakeholders' needs to potential robotic missions in extreme terrain, in the context of a permanent lunar settlement evolving out of the planned Artemis Base Camp [3]. These needs could be summarized as, a reliable capability to safely traverse various types of extreme terrain, including highly porous and/or highly inclined regolith, PSR's and lava tubes [4], while carrying payloads a few times the mass of the robot. Speed was not a requirement, since most missions did not require excessive back-and-forth travel, and those that did would likely include the construction of roads in their concept of operations. From this starting point, we brainstormed many possible bio-inspired robot forms that might meet these needs while accomplishing each of these missions.

2.2 Mission Scenario / Use case

To down-select among the several pairs of missions and robot forms we had generated, we were guided equally by stakeholders' needs as analyzed above, and by four main overarching programmatic / strategic principles that we selected following the end of our brainstorming phase:

1. versatility, for applicability to more than one mobility use case;
2. scalability of the concept, to carry payloads from kilograms to tons;
3. competitive applicability to a real, near-term operational scenario; and,
4. feasibility of a first demonstration in the 2026 timeframe.

Selecting a concept consistent with all of these principles and with stakeholders' needs involved numerous strategic discussions, feedback sessions, and incremental steps. Based on our background research and on our analysis of stakeholders' needs for robotic mobility, the team sketched a handful of potential use cases. These were described in our proposal, and included geotechnical characterization and emplacement of infrastructure in extreme terrain, performing a preliminary robotic exploration of unexplored extreme terrain, and the capability to provide power and communications between infrastructure outside extreme terrain, such as landers or surface power systems, and assets inside extreme terrain, such as instruments, rovers or fixed engineering services. After a first review of alternatives, we selected a concept that appeared to add the most value to other missions: that of providing a recharging capability to other robots operating inside a PSR by unspooling a power cable while walking through extreme terrain so as to reach a location inside a PSR that would be accessible by wheeled rovers operating inside.

At that point, we realized that there was an opportunity to decompose our various bio-inspired robots, not just for this use case but for *all* our use cases, into a very small number of common elements, key among them being a Worm-like robot. We observed that a suitably designed Worm could carry out many of the functions of a leg, arm, backbone, tail or neck, with only a change of software. With only a small number of common elements at the subsystem level, it would be possible to develop a platform instead of a single robot, meeting the needs of our recharging station use case, shown in Fig. 3, and potentially of several other use cases. We also felt that the versatility and interoperability provided by a reconfigurable, interoperable robotics platform would democratize the playing field for lunar robotics, lowering barriers to entry and spurring innovation by small companies for add-on components compatible with our envisaged worm-centric platform. Thus, in mid-November 2021, we decided to design and build WORMS.

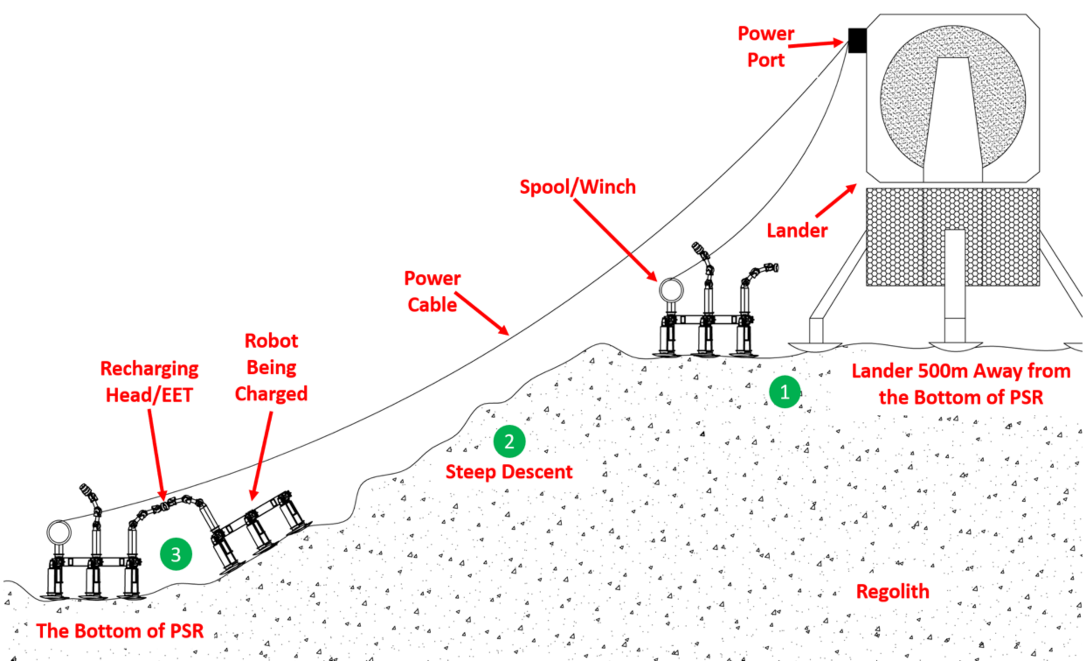


Figure 3 Setting up a Charging Station inside a PSR for other robots or rovers [5]

3 Project description

3.1 Results Overview

The implementation of WORMS between March and October 2022 met our key objective of reaching TRL 4 by demonstrating the feasibility and functionality of a reconfigurable robotics platform. We demonstrated that a field-assembled robot itself consisting of six independent 'Worm' robots could bear static as well as dynamic loads. We showed that we could synchronize Worm movements to walk on level ground. Having demonstrated that our 120kg robot could bear its own weight, our calculations showed that it could carry ~3.5 times its own weight on the Moon. Moreover, we demonstrated power-sharing between the independently-powered Worms and made a map of the robot's surroundings in the lab using a modular 'species module', with all command-and-control messages being exchanged using the ROS 2 (Robotic Operating System 2) framework.

Our testing program, by way of numerous subsystem tests and 17 integrated tests, made it possible to advance the state of the art by demonstrating that a reconfigurable robot platform could be used to easily assemble a functioning hexapod robot that is made of six independent robots. We believe that our platform approach to lunar robotics is competitive and cost-effective, as the standardization to a very small number of elements used by the platform ought to unlock savings over time in the amortization of robotics non-recurring DDT&E; in crew operations and materials; due to mass production, the learning curve, minimization of obsolescence, high reuse, and to increasing reliability of new Worms, and finally due to the significant simplification of in-the-field maintenance, which is reduced to swapping out faulty units and shipping them back to Earth for inspection and refurbishment.

The same characteristics of the platform make it operationally resilient, as new robot configurations can be created as a 100% software project to respond to unknown – unknown operational needs, and offer multiple ways to recover from contingencies or emergencies, such as an astronaut replacing a damaged leg of a (Gen2) robot in the field, or any one of the six radios of a hexapod being able to communicate back to base.

The technology can be ready in time for a 2026 demonstration, because the only truly new component is the Universal Interface Block: most of our innovations lie in the architecting of the platform. The required power systems, actuators, rad-hardened avionics and thermal protection systems for a flight demonstration can likely be sourced from components with flight heritage.

Moreover, the Gen1 Worms robots can easily scale up to serve other operational concepts, such as relocating or constructing habitats, or deploying ISRU equipment. In our roadmap of three generations of Worms, detailed in Appendix I, Gen3 worms would have a mass of ~60kg each, which feels like 10kg on the Moon so astronauts can still field-reconfigure them by hand. Yet, a Gen3 hexapod similar to our WORMS-1 proof of concept could carry a payload of up to nearly ~1.9 tons on the Moon – several times its own mass.

Finally, the WORMS architecture has enough surplus processing and communications power (at least one computer and one radio per worm, so at least six per hexapod configuration) to share the edge computing and data transfer burdens of operating in an environment where communications may be interrupted, have high latency or limited bandwidth.

3.2 Description of the concept

3.2.1 Concept lifecycle and design assumptions

As discussed, our team took a long view of the system lifecycle, and broadened the system boundary to include all uses of robots on the lunar surface. Our major design assumption was that, in the absence of a platform, a zoo of incompatible robots would end up cluttering Artemis Base Camp and its surroundings a few years after the establishment of the outpost, and that this could turn out to be a costly missed opportunity for NASA and for its international and commercial partners. Thus, we expanded our original 'versatility' design principle to go beyond serving "more than one" mobility use case, to serving "nearly all" mobility use cases. Setting the bar at this high level led us to designing a Lego-like platform architecture for reconfigurable robots that could meet not just extreme terrain mobility needs, but ultimately – with the right species modules and accessories – almost any mobility needs. Moreover, since worms can emulate the functions of not only legs but also arms, backbones, necks and tails, it follows that the applications and concept lifecycle of the WORMS platform are not restricted to mobility, but can also add value to lunar construction, lunar warehouse management, lunar industry and generally to any lunar surface application where a robot could be deployed.

3.2.2 *Major development, testing, and implementation decisions*

A fundamental development decision we made early on was to plan on paper a comprehensive roadmap for technology development (see, e.g., Appendix I, which lists the features of three generations of Worms), while also recognizing that the starting point for a technology demonstration was getting a robot made out of robots to demonstrate a basic mobility capability of walking a short distance on level ground. Hence for this phase of WORMS development between March and November 2022, we made the following major development, testing and implementation decisions, summarized in Table 1 below:

Table 1 Summary of Major Development, Testing and Implementation Decisions

Type of Decision	Made when	Decision details	Explanation
Development: restrict scope to focus on validating and demonstrating only the essential platform-enabling capabilities	March 2022	Demonstrate Universal Interface Block (UIB), including mechanical, power and data interfacing	Following submission of the proposal, we received feedback from judges and mentors to limit the scope of our project. As a result, we re-focused our development priorities as shown.
		Demonstrate three types of shoes (folding, flat and/or Apollo-like footpads)	
		Develop a classic hexapod for better stability, with the minimal degrees of freedom per worm	
		Demonstrate communication and coordination between six Worms	
		Demonstrate power sharing capability using an active four-switch flow controller	
		Demonstrate walking capability by walking a short distance in lunar regolith simulant	
	April 2022	Demonstrate one type of shoe (Apollo-like), one accessory (pallet) and one species module (LIDAR)	During design development, it was felt that our resources would be better spent by tweaking our plan to cover all essential elements of the architecture as shown.
		Demonstrate only the mechanical interface functionality of the UIB	
	May 2022	Demonstrate walking capability by walking three body lengths over the lab floor	
	June 2022	Modify the pallet so that legs on two sides are parallel	
	Aug 2022	Demonstrate a passive power sharing capability using only natural dynamics	Late decision made after facing testing difficulties with the flow controller.
Testing: facilitate fast and safe hardware-in-loop software testing	April 2022	Develop a two-leg wave walking gait in the Gazebo / ROS simulation environment so as to test the code in a sim before testing in hardware	Initial plan for safe hardware-in-loop testing
	June 2022	Developed a new walking gait inspired by the way turtles walk, dubbed "Magic Carpet"	Early attempts to adapt an existing 2-leg wave gait did not work as well as needed
		Perform early hardware-in-loop software testing with the 100+ kg robot suspended from a gantry crane and also fixed to a welding table ("air-walking")	Improved testing plan, a shortcut to being able to do both more and safer hardware-in-loop testing
		Walk on floor only with code previously demonstrated by air-walking on the table	
Implementation: allocate sufficient resources for	April 2022	Re-allocated budget originally intended as a stipend to graduate students to hire six paid Undergraduate Research Opportunities Program (UROP) students who would build all the hardware and power	Following the completion of the detailed design, it became apparent that demonstrating the concept

building out all the required demonstration equipment		distribution subsystems and harnesses for six independent Worm robots, six shoes and the pallet.	would require substantial machining and electrical labor capacity.
	June 2022	When machining was progressing slower than anticipated, the decision was made to sub-contract the CNC milling of the UIB's to an external vendor	
	July 2022	Recruit an additional team member to develop the LIDAR Species Module	

Of all the scope decisions, our focus on developing, testing and validating the UIB mechanical interface was the most central to demonstrating the architecture. Having an androgynous mating point was crucial to our vision of modularity for WORMS. This ensured that our design could scale with future iterations, and that the same component found at the two ends of a worm could be moved around to different spots on the pallet, on payloads, or on species modules. Our CONOPS talks of scenarios inspired by elephants walking tip to tail, connected to share power and stability or attaching a winch and cable to the top of the pallet. These mission scenarios are made possible by having an interface that is universal to our ever-expanding fleet of WORMS and accessories. In our proof-of-concept, these UIB's are permanently attached to the pallet in desirable locations for legs or sensors, as well as on the ends of each worm. This allows a worm to attach to the pallet, but also have an end open to attach to shoes or other WORMS. The UIB, fitted on a selection of body shapes, shoes, and species modules, makes it possible for shoes, bodies and specialized capabilities to be chosen to suit mission requirements terrain.

3.3 System decomposition and description, by subsystem.

The proof-of-concept WORMS-1 robot decomposes into five main subsystems as shown in Fig. 4 below. Note that the subsystems physically integrated with the robot all feature at least one UIB.

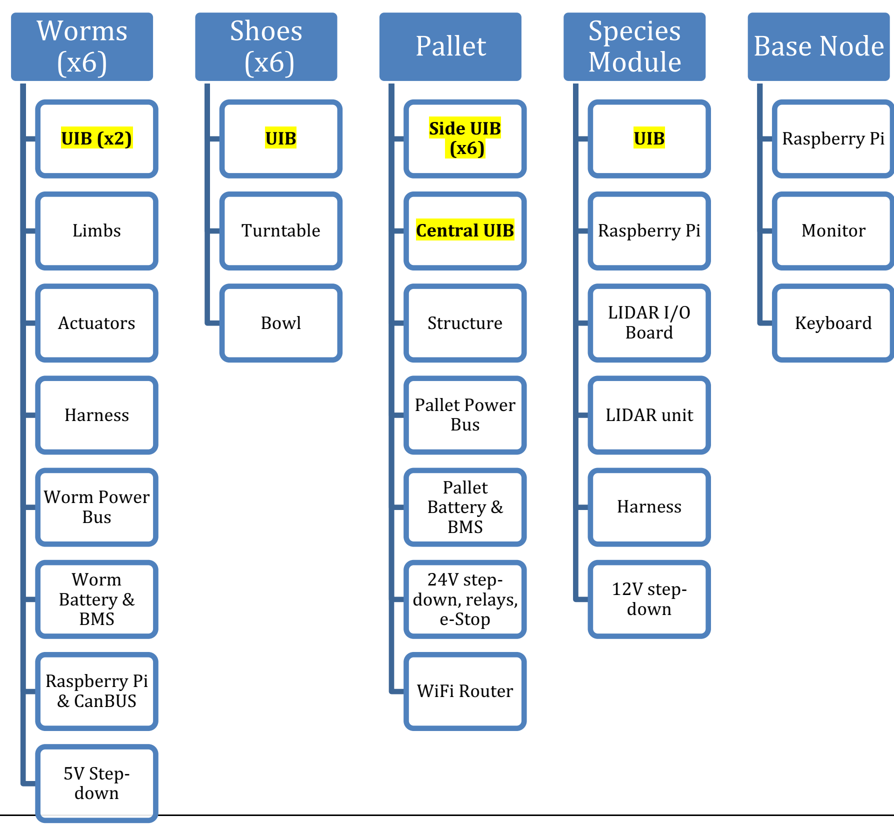


Figure 4 WORMS-1 proof-of-concept system decomposition

3.3.1 Universal Interface Blocks (UIB)

We designed a Universal Interface Block (UIB) to connect the Worm with other components of the robots, such as the pallet, shoes, and species modules. Therefore, mechanically, firm connection is required at the UIB interface under a maximum design load of 150 N shear force and 106 Nm bending moment. To satisfy this requirement, as shown in Figure 5, finite element analyses (FEA) were performed using Abaqus CAE structural solver; and the dimensions of UIB were selected accordingly with a safety factor to yield of around two. Aluminum 6061-T6 was selected eventually from a tradeoff between weight and strength requirements. In addition, experimental structural tests were performed with the final UIB design, by loading the UIB interface with a 216 N of shear load and 108 Nm of bending moment as shown in Figure 6. The loading-unloading process was repeated four times, and no visible structural damage observed.

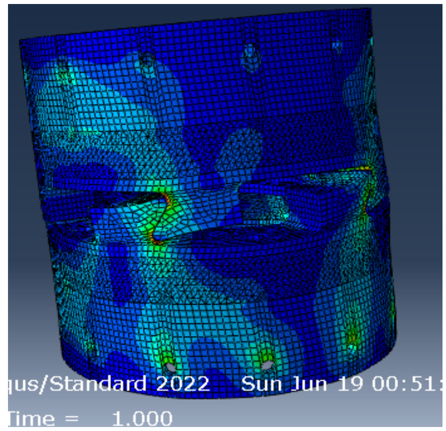


Figure 5 FEA of UIB

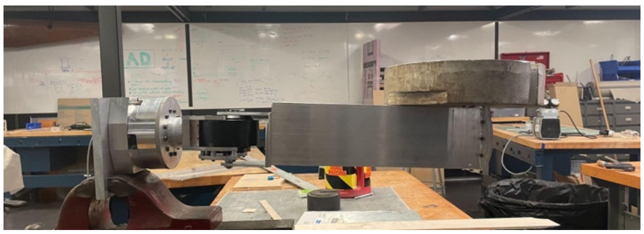


Figure 6 Structural Tests with final UIB design

Architecturally, it is required for the UIB interface to be androgynous and rotationally symmetrical for the ease of reconfiguring worms, accessories and species modules into new robots by easily disconnecting and reconnecting components in the field. Thus, as shown in Figure 7 a jaw-pin connection mechanism was eventually selected such that the pins would automatically lock in place once the jaws rotate into each other. An odd number of jaws was selected to minimize the number of jaws located near the neutral surface in bending. Then, the 45-degree jaw angle and the flat jaw slant surface were selected from the balance of space and manufacturability. In Gen1 design, the locking pins are spring plungers which require external decouplers to disconnect the interface as shown in Figure 8; however, as described in Appendix I, motor actuated locking pins would be implemented in Gen3 design to realize an autonomous coupling-decoupling process.

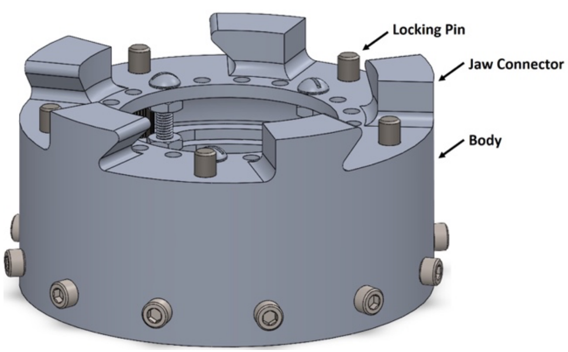


Figure 7 First design of UIB - overview

The third fold of requirements stems from the functional aspect that the UIB shall reserve space for the installation of potential species modules. Therefore, as shown in Figure 9, empty space was reserved in the center of the UIB. There are mounting holes on the top surface of the UIB for the anchoring of any extruded species module into the jaw region. Internally, there are lightweight suspension bolts and suspended decks for the installation of locking pins, chips for species modules, and batteries for additional power supply. Multiple suspended decks can be customized and fitted in to accommodate different configurations of species modules.

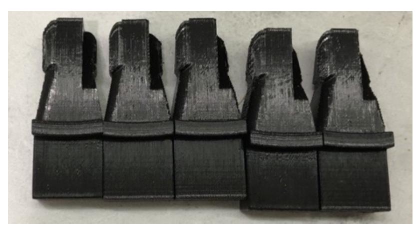


Figure 8 Set of five decoupling tools, required for Gen1

The initial in-production design, as shown in Figure 9, centered around the minimization of computer numerical control machining (CNC) with the intention of reducing the production cost and difficulty. The structure can be dissected into three portions, the jaw connectors, the top plate, and the cylinder body, each of which was supposed to be turned from an annular aluminum workpiece. The connection of the three portions were realized using 8 pieces of stainless-steel angle brackets. This design was soon found to be problematic. Structurally, extreme concentrated stress appeared on the corners of angle brackets, making the design structurally unfavorable. Production-wise, the bolt slots on the top of the jaws had a complicated shape which can hardly be created using a manual vertical milling machine. In addition, the vast use of stainless steel angle brackets made the design overweight. Therefore, CNC was utilized in the second design and the production was outsourced to an external company. As can be observed from Figure 10, the second design with the use of CNC machining, contained a lot more flexibility to reduce the weight and enhance the structural strength using fillets and cavities. However, the size of the jaw connector was still constrained by the dimensions of the available dovetail cutter on market; and the geometries of certain components were still simplified to make them machinable using less expensive techniques such as the waterjet.

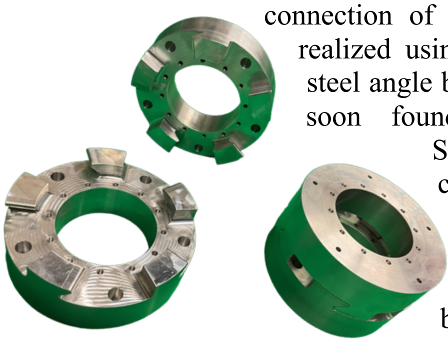


Figure 9 Final design of UIB for CNC mill

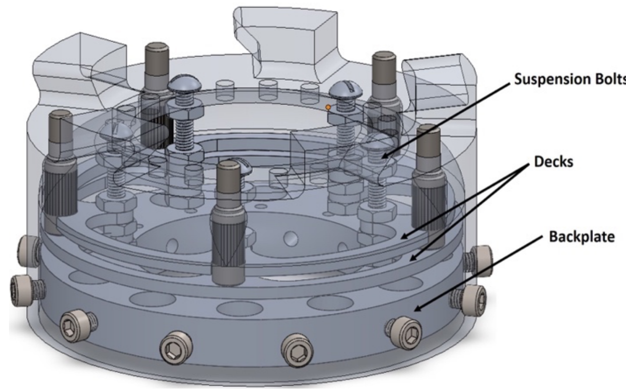


Figure 10 First design of UIB for waterjet and manual mill

3.3.2 Gen1 Worm Robot Structures

We formulated the Gen1 Worm robot's requirements to focus development on the system's key technologies and mitigate risk of structural failure during testing. Thus, we chose to develop a hexapod, which provides more stability on inclines. Additionally, we chose to minimize the Gen1 Worm's degrees of freedom in order to accelerate production and testing. In a hexapod, the legs need a minimum of 3 degrees of freedom to maneuver on uneven terrain. A prototype leg, shown in Figure 11, was constructed to visualize leg movement.

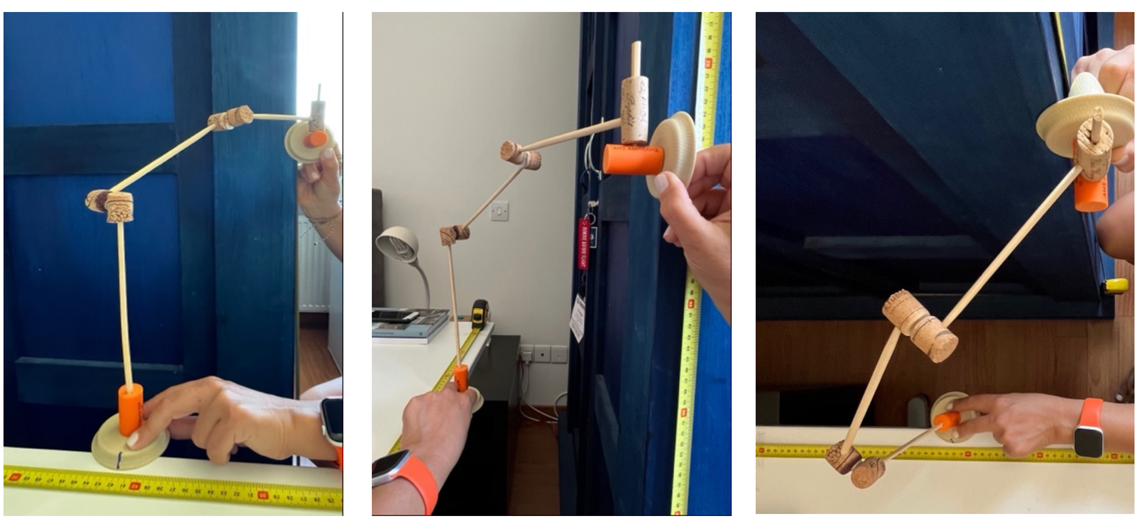


Figure 11 Prototype leg in kinematics test using chopsticks, sewing needles and corks: side, back and top views.

Finally, we restricted our actuator search to commercial off-the-shelf (COTS) actuators with integrated motor, gearbox, and control electronics. With a limited development timeline, COTS actuators let us focus on the project's primary development tasks and drastically reduce risk of actuator failure. We iterated through dozens of combinations of limb lengths, limb masses, payload masses, and actuators using the Hexapod Actuation Tool [6]. This tool primarily estimates the required torques at each actuator throughout the gait. With some modification to the tool's code, we also estimated the gait's actuator current draws, which fed into initial power distribution requirements. An example of these torque and current profiles are shown in Figure 12. At each iteration, structural hand calculations were also used–by approximating limbs as beams, columns, and shafts–to increase confidence in our limb mass estimates. By prioritizing availability, low mass, continuous torque rating, maximum speed, cost and documentation, we selected the T-MOTOR AK80-64 actuator from three COTS actuators, summarized in Table 2.

Table 2 Actuator Selection [7]–[9]

Actuator	Max Continuous Torque @ 48 VDC [Nm]	Speed at Continuous Torque [rpm]	Mass [kg]
Harmonic Drive SHA25A SG	28-81 (varies with gearing)	75-24 (varies with gearing)	3.1
Rozum Robotics RDrive 85	108	40	2.47
T-MOTOR AK80-64	48	57	0.85

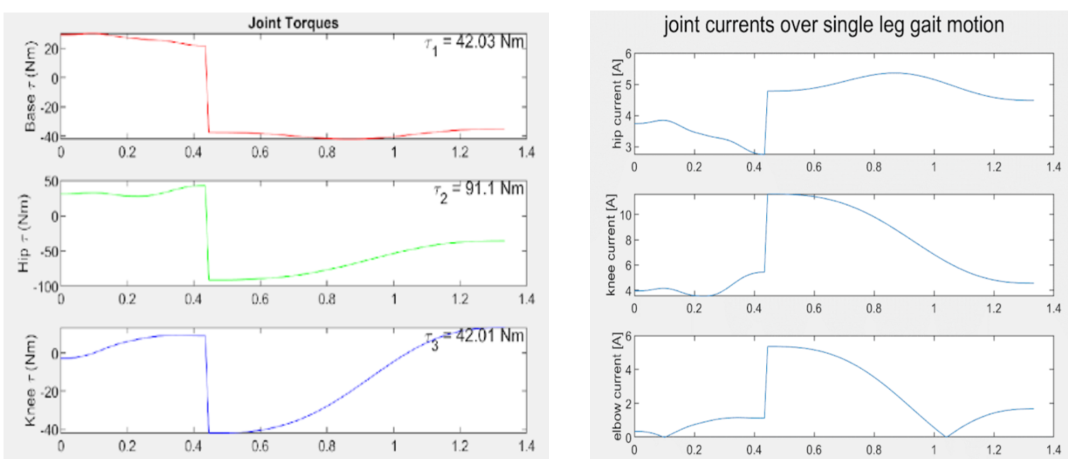


Figure 12 Modeled joint torques and currents informing actuator selection

With an initial sizing for the WORMS-1 robot, including actuators, we completed a detailed design of the Worm structure. We prioritized simple manufacturing – such that we could mass-produce these robots for our demonstration – and high strength margins. Although increasing strength margins decrease the robot's payload capacity, we wanted to reduce the risk of structural failure throughout the integrated testing period. We selected aluminum alloys for their high strength to weight ratio, relatively low cost, and excellent machinability. Load cases were defined to design the limbs. Using a statics model, depicted in a free body diagram in Figure 13, the leg's internal moments and forces were estimated throughout the gait on horizontal ground and 30-degree inclines. All structural parts were designed with safety factors to yield > 3 to account for dynamic effects and uncertainties in our calculations. A common limb design was used for all limbs; only a limb's tube length was modified to achieve a different limb length. Thus, we performed detailed finite element modeling only on the hip structure and coxa, which experience the largest internal moments of the limbs. From this analysis, we concluded that the Gen 1 Worm design mitigates risk of structural failure during walking tests.

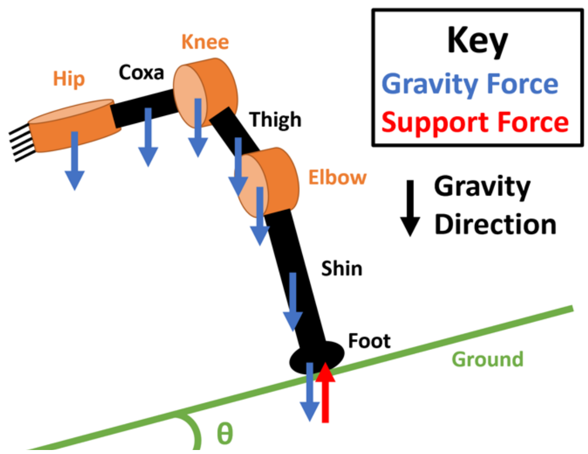


Figure 13 Free-body diagram used to model torques at each actuator and define load cases on each limb

3.3.3 Worm redesigns necessary for mass manufacturing

Two major design changes were made to the Worm's structure to accommodate the limitations of in-house machining capabilities and time constraints: one pertaining to the part that integrated each motor to a worm robot, and the second to the angle brackets that connected to the motor and enabled each motor to move the overall structure.

The initial worms design fixed the actuators to the rest of the Worm's assembly with a single part. However, upon further inspection and consultation with machinists, it was revealed that fabricating this part for each actuator using in-house manual and CNC milling would both take too much time and introduce a high degree of variability between each copy. As a result, the component was broken into a subassembly of two ¼" plates that sandwich the actuator, Fig. 14, held together with a ½" plate that would connect to the various tubes comprising a single Worm's structure.

Figure 14 Final worm design, as-built, shown here with UIB connections to the pallet (above) and a shoe (below)

3.3.4 Shoes

The shoes were designed to navigate the highly porous regolith found at the lunar poles, but can be exchanged to suit whatever terrain is needed. Three types of shoes were tested in a highly porous simulant. Our primary shoes were based on the Apollo Lander's foot pads in concept and dimension, as shown in Fig. 14. Because the use case was similar, sitting atop regolith, we sized down the dimensions to support the weight of our robot. The bowl shape was intended for increased traction and support while navigating the highly porous terrain, as well as for safer reaction of loads when walking over rocky terrain.

3.3.5 Pallet

Design principles. Two main functions of the pallet were to provide a body frame for the WORMS-1 hexapod and to carry payload. The main design-guiding principle was to reduce the pallet's mass while maintaining its structural strength against large loads and torques as well as ensuring that there is enough space between the Worm legs to support the walking gait.

Design iterations. The pallet designs considered included both single and double layered pallet structures. First, a single hexagonal pallet consisting of honeycomb aluminum was considered. However, there were issues with the mass as the fully filled and thicker pallet mass exceeded 14.47 kg. So, a double layered approach was taken. The initial pocketed hexagonal pallet plates were 1000mmx1000mm wide; iterations to the extrusion supporting the two pallet plates included hollowed rectangular extrusions and a truss-inspired approach (see Fig 15, left). The total mass of the pallet with the UIBs included was 10.08 kg for this version (fasteners are not included in this estimation). After optimizing for expected loads and manufacturability, and implementing additional mass-reduction measures, the total mass of the pallet was reduced from 10.08 to 7.74 kg (see Fig. 15, middle). The next major iteration was implemented to adjust the design to the developed 'parallel-legged' gait, with the 3 leg UIB pairs now spread along the longer dimension of the pallet and spaced at different distances from its central line so that to decrease the likelihood of the individual leg Worms interfering with each other during walking (see Fig. 15, right). This final design consisted of a double layered pocketed rhombus of dimensions 1291x1000 mm with 121 mm offset between the pallet plates. It was constructed of two ⅛" thick Aluminum 7075-T6 plates that sandwich six Aluminum 6061-T6 I-section supports and six UIB housings to reduce mass. The total mass of the final version was 7.67 kg (without fasteners).

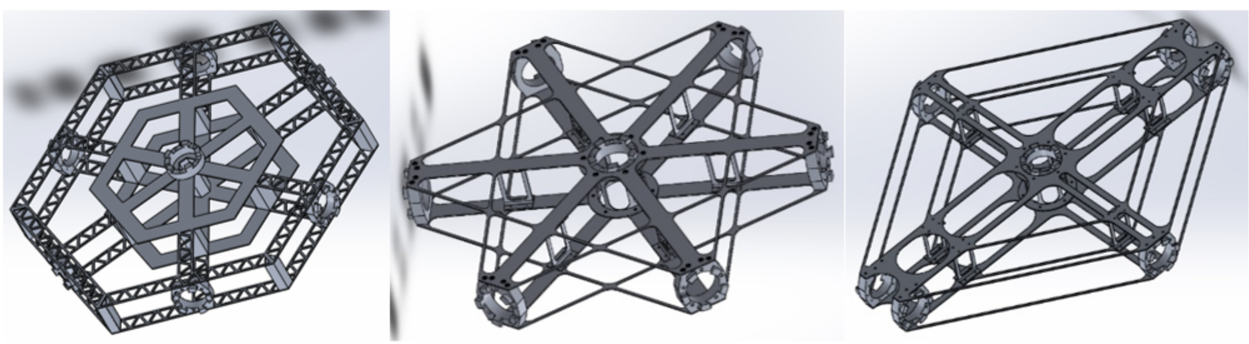


Figure 15 Evolution of the double-layered pallet design.

Load cases and strength analysis. The statics model was used to estimate the forces and moments acting on the pallet at two main stages of the walking gait: raising a front and an opposite rear leg (load type 1), and raising the two middle legs (load type 2). Additionally, 1-g gravity field acting on the pallet was simulated and an additional mass of 19.34 kg was applied to the center of the pallet to simulate the pallet payload mass.

Finite element analysis showed that the stress values on the pallet elements were larger for type 2 than for type 1 loads (see details on both load cases and the respective simulation results in the Verification Documentation). The minimum safety coefficient for the pallet assembly is 3.26 (for the neck UIB); the maximum displacement is 4.3 mm. Thus, the pallet was designed to have a safety factor to yield > 3.

Pallet payload. Apart from the Mapper species module attached to the pallet's central UIB, the pallet carries a router, a power distribution board, the e-Stop switch relays, power and data cables, a battery with a BMS and three step-down transformer, all of which were placed and fastened inside the pallet structure with velcro fasteners, plastic zip-ties, or, in some cases, screwed to specially designed for that purpose plastic boards attached to the pallet.

Pallet power bus. A power distribution board with cabling terminated at each of the six leg UIB's supports the parallel interconnection of the power buses of all worms which are connected to the robot.

3.3.6 Species Module

To exemplify a species module for the WORMS platform, a "Mapper species module" was designed and built. This module modifies the base end effector mechanical design, for maximum modularity and similarity to other future species modules with the internal electronics mounted inside the end effector on a 3D-printed PCB rack. In the Gen 1 Mapper module, a Velodyne VLP-16 LiDAR unit is included, along with a Raspberry Pi and interface board. The Mapper module receives power from the 48V pallet power bus via a 12V step-down transformer installed on the pallet, and does all its own processing, transmitting the point cloud through the ROS 2 framework and displaying it in RVIZ on the base node. In future generations, species modules will have their own power sources. The software enhancements to the Gen 2 Mapper module (same hardware as Gen 1) will be capable of performing obstacle detection, with possible extension to sensing large terrain features so that the gait may be modified on hilly terrain and around obstacles.

Figure 16 "Mapper" Species Module

The design of the Mapper species module for the Gen 1 WORMS system provides a template that may be used for other types of species modules. Indeed, a similar packaging scheme with a self-contained processor and electronics systems can be used to package a winch system species module.

3.3.7 Base Node and Software Architecture

The ROS 2 software architecture is a centralized communication system used to manage the communication, control, and operation of autonomous robotic systems. Due to ROS 2's increased capability for multi-agent autonomy and cross computer communication, it was decided that it would be used as the middleware that would define the software architecture for WORMS.

All communication and operation is defined by commands entered by the user through the "Base Station", a primary node that both receives and transmits data to and from each individual Worm through topics. This data is packaged into messages that represent core information about the state of the system and the commands being executed. The primary feedback received from each individual WORM include "Robot_Info", "State", and "Heartbeat" which are all indicators of either nominal or un-anticipated performance; see Fig. 17.

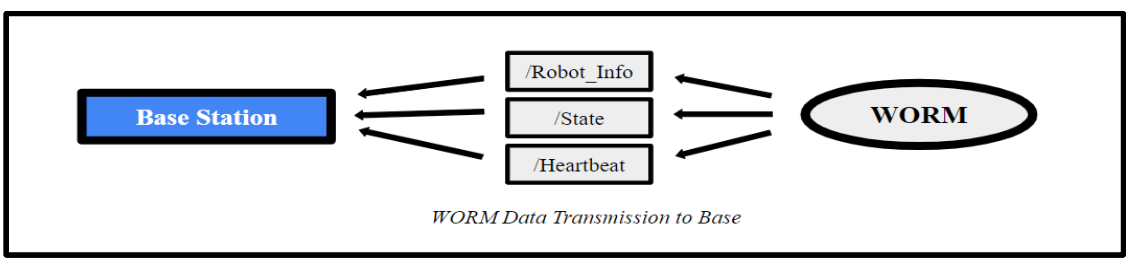


Figure 17 Feedbacks received by base station (controller) node

- **Robot_Info:** Contains important raw data regarding motor encoder position, velocity, and torque for all actuators on a given worm.
- **State:** Used as a numerical indicator of whether a given worm robot is executing a specific phase of the gait, has successfully completed motion, or is steady and awaiting a command.
- **Heartbeat:** The lifeline of the system and the status of the communication line between the base station and a given worm robot.

In order to assure safety and intended performance, all control and actuator motion is reliant on the existence of the heartbeat flag. If the flag is not returned as true (alive), motors will deactivate and the software equivalent of an emergency stop will be taken.

Any cross-communication between worms happens through the base station, which is responsible for both publishing commands and receiving responses. In order to allow for a multi-configurable system, the base station can be hosted on either a separate operating machine or on one of the worms itself. This introduces the idea of a "base worm" which would be a worm that acts as the base station. With this method, the child worm channels are not polluted by excess data from its sibling worms. Instead, the child worms publish only to the base which executes checkpoints and commands its children to act synchronously.

Under this framework, the base station is responsible for allocating the necessary commands to each worm in order to execute the intended walking gait. This information is composed within a message that is sent over the "Command" topic that directs each individual worm's motion, as shown in Fig. 18. The other topic that is communicated between the base station and the worm is the heartbeat which was defined in the previous section.

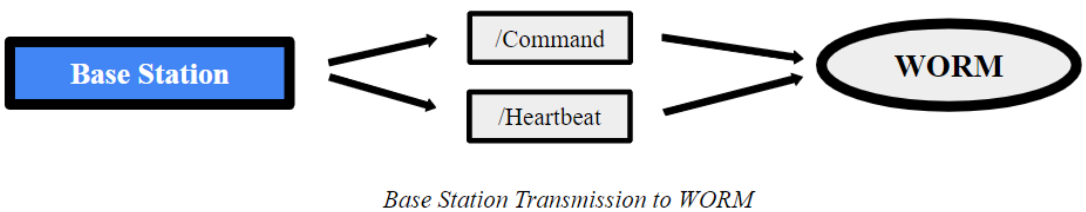


Figure 18 Base station transmission to worm

With each of the six worms having such communication with the base station, independent identification of each robot becomes very important. The walking gait requires specific worms to be moved based on their position on the pallet. Because of this, a numbering scheme for each specific "leg" of the pallet configuration has been defined and can be seen in figure 19.

3.3.7.1 The 'Magic Carpet' walking gait

The current generation of the robot moves using our Magic Carpet gait, which we developed from first principles. The Magic Carpet gait has two main stages: leg repositioning and propulsion. The leg repositioning stage has three steps. In the first, legs 1 and 4 (see figure 19) are lifted from the ground, moved forward, and placed back down. In the second, legs 2 and 5 are lifted, moved forward, and placed back down. Finally, legs 3 and 6 are lifted, moved forward, but not placed down until the propulsion phase occurs. The software for this code uses the T-MOTOR CAN library to control the motors. The commands include the desired position, velocity, K_p, K_d, and feedforward constants. During this stage, position commands are sent in set smaller intervals to allow for better control of the positioning and more feedback from the motors. To lift the legs, commands are sent to the motors to move the knee and elbow motors by the same angle in opposite directions to obtain a clean lift off the ground. When moving the Worm forward, commands are sent to the hip motor while the other motors hold position. Finally, to place the leg back on the ground, the knee and elbow motors are brought back to their original positions.

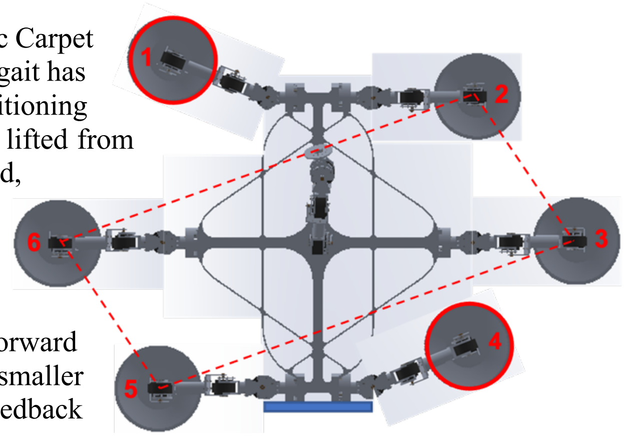


Figure 19 Leg numbering scheme and first step of magic carpet gait

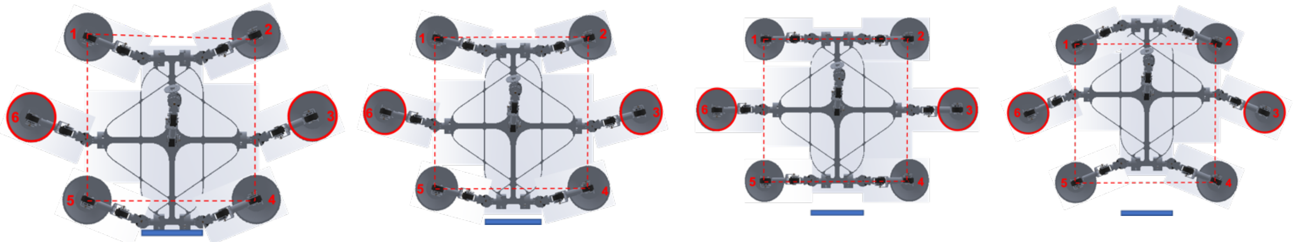


Figure 20 In the propulsion phase, the pallet pivots forward around the ankles while maintaining a fixed distance from the parallel lines of the shoes on each side.

During the propulsion stage, which resembles the gait of a tortoise, the body (pallet) of the robot moves forward, while the feet stay stationary on the ground, as shown in Figure 20. To achieve that, all the feet must move in a straight line parallel to the forward direction, relative to the body, maintaining a constant distance to the center line. The solution for this is moving the hip at a constant speed by steps of equal angle, and updating the angle of the knee and elbow using the following formula (up to a sign, depending on the worm number and the motor orientation):

$$v_1 = 90 - v_2 = \arccos\left(\frac{X - L\cos(h)}{M\cos(h)}\right)$$

where h, v_1, v_2 are the hip, knee and elbow angles respectively and X, L, M are the minimum lateral distance from the foot to the hip during the gait, the length of the hip-knee link, and the length of the knee-elbow link, respectively.

To control the speed of the motors, the robot uses a loop that changes position by a small amount in every iteration. The time between every iteration is inversely proportional to the speed of the motion. Since the motors do not have an integrator, position control is slightly dependent on external torques (i.e. the weight of the worms and robot). A gravity compensation algorithm is still in development, and is expected to significantly improve the accuracy of Worm motion.

3.3.7.2 Design of the Magic Carpet Gait

Each variable is parameterized such that we can estimate each actuator's torque throughout the gait with different environmental factors (gravity, local inclination angle), mechanical designs (limb lengths *l, m, n*, mass distribution), actuator specifications (continuous torque rating, speed at continuous torque, torque constant), and gait parameters (lateral distance of feet from hip joints *X*, hip full-swing angle *h*, knee and elbow angles v_1, v_2, number of legs lifted), as shown on Fig. 21.

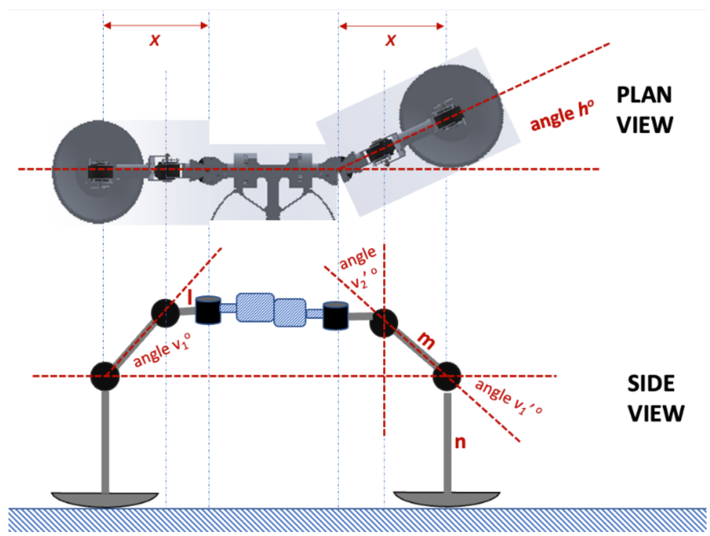
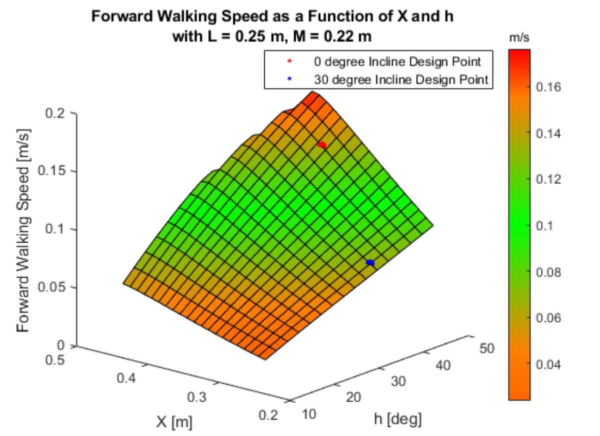


Figure 21 Parameters X, h, l, m, n, v1 and v2 used in Magic Carpet walking gait.

Our custom tool provides comparisons between three competing Figures of Merit: forward speed measured in meters per second, actuator continuous torque margin (dimensionless), and endurance, measured in meters of distance. These metrics are optimized using the goals and variables described in Table 3. In summary, we aim to maximize all metrics. However, these metrics are in tension and are also affected by common variables: some metrics are maximized when X increases but others are maximized when X decreases. For the Gen 1 Worm design, we performed a trade study of the first two metrics (forward speed and torque margin) to achieve the optimal design for our WORMS-1 mission. Figure 22 illustrates these trades and the iterative process that was followed to select a design point that had sufficient torque margin and good forward speed. Subsequent Generation Worm designs will be refined with a trade study of all three metrics, including Endurance, to identify non-dominated architectures that efficiently allocate the robot's limited resources among forward speed, safety margin and endurance.

Table 3 Figures of Merit for a walking gait



Metric	Goal	Variables to Control
Forward Speed	Maximize	Maximize X and h
Actuator Continuous Torque Margin	Maximize	Minimize X, minimize h on incline
Endurance	Maximize	Minimize X, minimize h on incline

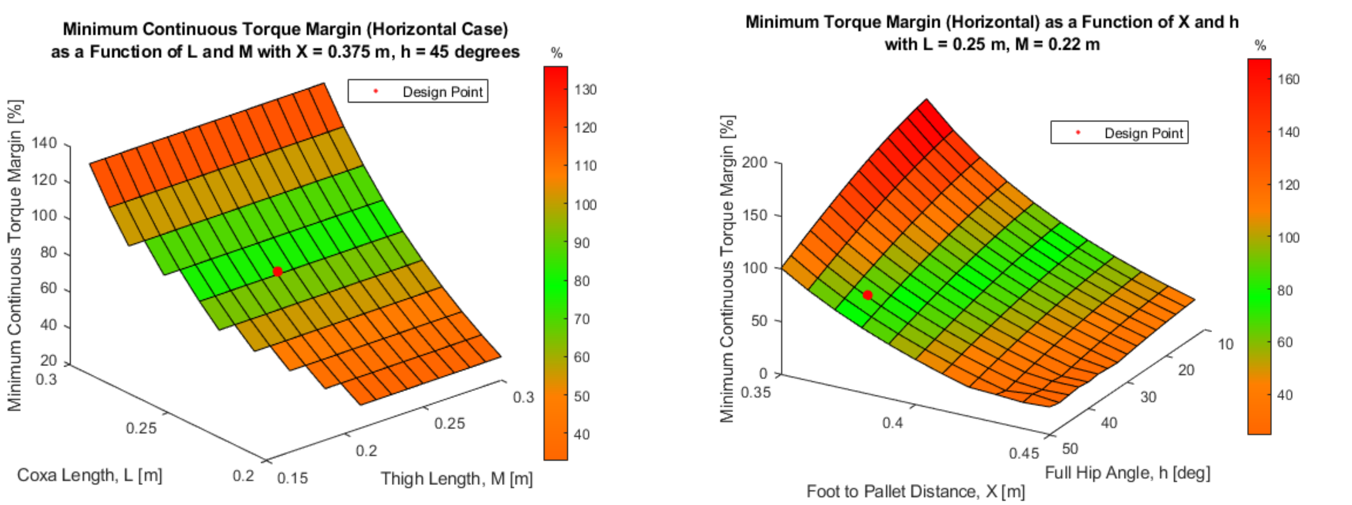


Figure 22 Trade of continuous torque margin vs forward speed in search for non-dominated design points for limb lengths (L,M) and software parameters (X,h)

Table 4 Projected endurance for WORMS-1 robot in lunar gravity at varying payload mass and inclines assuming max 40% depth of discharge

Local Incline	Endurance with 0 kg Extra Payload [m]	Endurance with 400 kg Extra Payload [m]
Horizontal	2404	441
30 Degree Incline	495	91

3.4 *WORMS Technical Specifications*

3.4.1 Volume (flat-packed)

When arranged in a "flat-pack" shape, as shown in Fig. 23, the seven Worms, six shoes, and one pallet can fit inside a volume of 0.82 m^3 (rectangular box of dimensions 1.4x1.7x0.4m). After the components arrive on the lunar surface, astronauts could assemble the full-scale WORMS-1 robot, which has a larger deployed volume. The IKEA® analogy extends further to the ease and speed of assembly by a non-specialist. A benefit of the field-assembled and reconfigurable WORMS architecture relative to classic robots is that parts for several WORMS robots can be shipped on a single flight, enabling operational concepts which require many collaborating robots. Such concepts may become more prevalent if the cost of launch mass continues to trend downwards.

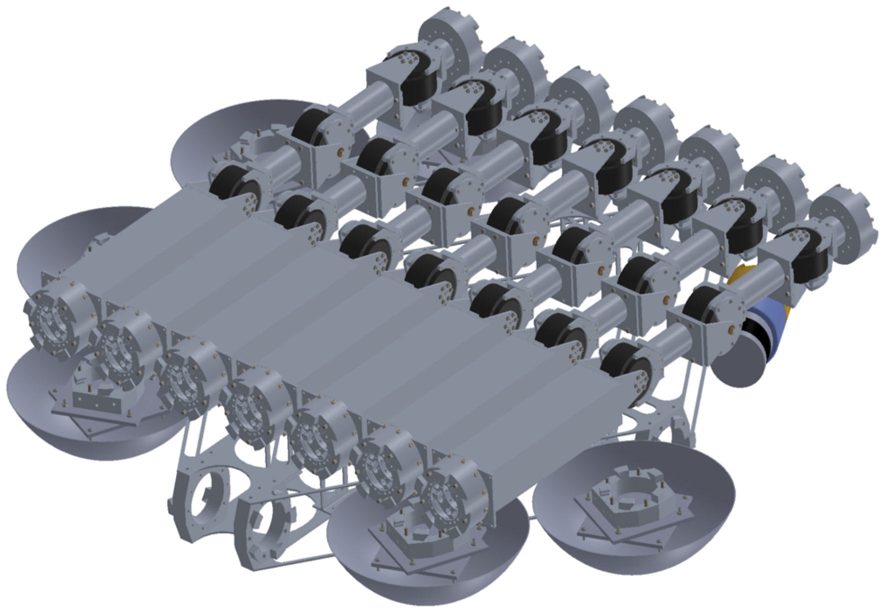


Figure 23 Flat-packed parts for a WORMS-1 robot

3.4.2 Mass budget (for one worm, and for WORMS-1 robot)

Table 5 Mass budget describing current design of WORMS-1 demonstration hexapod

Worm				
Subsystem	**Part / Assembly**	**Quantity per Worm**	**Mass per Part [kg]**	
End Effectors	End Effector (Pallet Facing)	1	0.73	
	End Effector (Foot Facing)	1	0.66	
Mobility & Articulation	Actuator	3	0.85	
	Hip structure	1	0.55	
	Coxa structure	1	0.86	
	Thigh structure	1	0.79	
	Shin Structure	1	1.86	
Accessories	Foot (UIB, Wok)	1	3.05	
Power	Battery	1	1.48	
	Battery Management System	1	0.09	
	Power sharing wires	2	0.08	
	Actuator Power Cables	3	0.03	
	Actuator Control Cables	3	0.01	
Software	Computer (Raspberry Pi)	1	0.05	
	R-Link (Actuator Connector)	1	0.03	
		Mass Per Leg	13.0	kg
		Pallet + Payload Mass	29.4	kg
		Total System Mass	117.2	kg

Pallet			
Category	**Part**	**Quantity per Pallet**	**Mass per Part [kg]**
Accessories	Pallet Structure	1	8.26
	Additional Payload Mass	1	0.00
Power	Pallet Batteries	2	1.48
	Battery Management System	2	0.09
Software	LIDAR Housing	1	1.90
	LIDAR Electronics	1	0.10
	LIDAR Computer (Raspberry Pi)	1	0.05
	LIDAR UIB	1	0.60
	Ethernet Cables	8	0.04
	Router	1	0.09
Payload	Payload	1	15

3.4.3 Power budget for Generation 1 Worm.

Table 6 Power Budgets - Earth version, no payload; Moon version, 400kg payload

Earth environment, no payload

Leg Worms			
Category	Item	Power [W	Notes
Walking	Actuator Power, Horizontal	124.5	Average
	Actuator Power, 30 Degree Incline	296.9	Average
Shin Package	Computer (Raspberry Pi)	15	Max
	Computer Fan	0.4	Average
	Voltage Regulator	1.77	90% efficiency
	IMU	0.10	Average
	Tinkerforge Interface Board	0.41	Average
	BMS	0.85	Average
	Total Average Power, Horizontal	**143.0**	
	Total Average Power, 30 Degree Incli	**315.4**	

Neck Worm		
Item	Power [W]	Notes
LIDAR	8	Average
Computer (Raspberry Pi)	15	Max
Computer Fan	0.4	Average
Voltage Regulator	2.6	90% efficiency
IMU	0.10	Average
Tinkerforge Interface Boar	0.41	Average
BMS	0.005	Average
Total Average Power	**26.5**	

Case	Quantity	Value	Unit
Horizontal	Walking Speed	0.143	m/s
	Time to Traverse 100 m	699	s
	Leg Worm Energy Consumed	28	Wh
	Neck Worm Energy Consumed	5.1	Wh
30 Degree Incline	Walking Speed	0.0702	m/s
	Time to Traverse 100 m	1425	s
	Leg Worm Energy Consumed	125	Wh
	Neck Worm Energy Consumed	10.5	Wh

Lunar environment, 400 kg payload

Leg Worms			
Category	Item	Power [W	Notes
Walking	Actuator Power, Horizontal	112.1	Average
	Actuator Power, 30 Degree Incline	267.4	Average
Shin Package	Computer (Raspberry Pi)	15	Max
	Computer Fan	0.4	Average
	Voltage Regulator	1.77	90% efficiency
	IMU	0.10	Average
	Tinkerforge Interface Board	0.41	Average
	BMS	0.70	Average
	Total Average Power, Horizontal	**130.5**	
	Total Average Power, 30 Degree Incli	**285.8**	

Neck Worm		
Item	Power [W]	Notes
LIDAR	8	Average
Computer (Raspberry Pi)	15	Max
Computer Fan	0.4	Average
Voltage Regulator	2.6	90% efficiency
IMU	0.10	Average
Tinkerforge Interface Boar	0.41	Average
BMS	0.005	Average
Total Average Power	**26.5**	

Case	Quantity	Value	Unit
Horizontal	Walking Speed	0.143	m/s
	Time to Traverse 100 m	699	s
	Leg Worm Energy Consumed	25	Wh
	Neck Worm Energy Consumed	5.1	Wh
30 Degree Incline	Walking Speed	0.0702	m/s
	Time to Traverse 100 m	1425	s
	Leg Worm Energy Consumed	113	Wh
	Neck Worm Energy Consumed	10.5	Wh

3.5 *Integration and Synergies of Concept with NASA Lunar Strategy*

By developing a modular system architecture which supports a variety of robot designs tailored to specific extreme terrain landscapes and missions, WORMS will provide a foundational mobility capability for future lunar exploration and development, covering the needs of the Artemis program as well as feed-forward applications to Mars exploration. In our proposed 2026 Gen1 technology demonstration, the WORMS-1 mission will provide power and data relay between the lander (supplier) and other robots and instruments (customers) within a hitherto unexplored PSR. Post-2026, reconfigured WORMS robots can help interconnect assets in a lunar power grid, such as solar panels on high ridges with habitats on the plains. In fact, NASA and partners are working to develop vertically deployable solar array systems for the lunar surface (LVSATs) [10], [11]. The hope is to use this power source to establish a sustainable presence at the lunar South pole. WORMS can support this mission by providing a way to transport these technologies to optimal locations, which may be at higher altitudes and require mobility solutions that can traverse slopes with heavy payloads. Longer term, as the human presence starts to grow, WORMS robots can help interconnect assets in a lunar power grid, such as solar panels on high ridges.

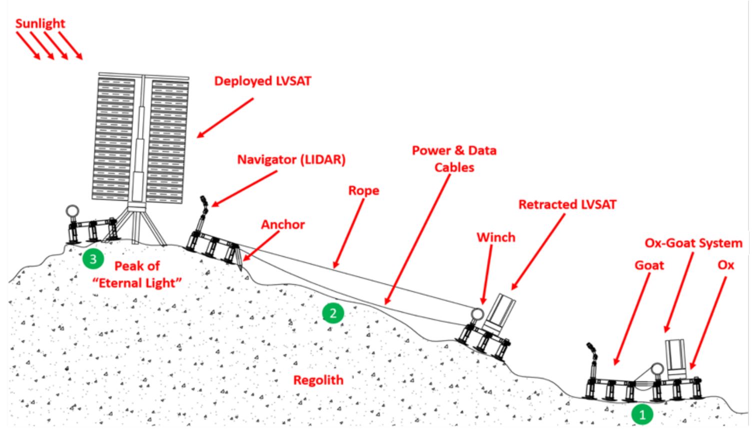


Figure 24 Two WORMS robots cooperate to deploy heavy solar arrays on Peaks of Eternal Light

This application would require a Gen2 WORM for its species module functionalities. and 900kg payload capacity in a hexapod configuration (Appendix I), making it a great system to carry large, heavy payloads such as LVSATs. First, the skilled climber - the goat - will traverse up the hill, anchor at the top and assist the heavily laden "ox" to climb using its winch Species Module. The WORMS software architecture will be leveraged here to provide the coordination between the two "separate" goat and ox WORMS robot configurations.

In Figure 25, a Gen3 WORMS carrier with an expanded payload capacity of 1.9t will first carry a lightweight Gen2 / Gen1 WORMS walker to the edge of a lava tube skylight opening. The WORMS carrier will then anchor itself using a drill from one of its arms and deploy the walker down to the floor of lava tube. The deployment will be performed using a cable winch mounted on a "crane" worm of the carrier. Both the drilling and winching motions will be realized by the rotation of the end effector around its axis, a degree of freedom enabled in Gen2 development.

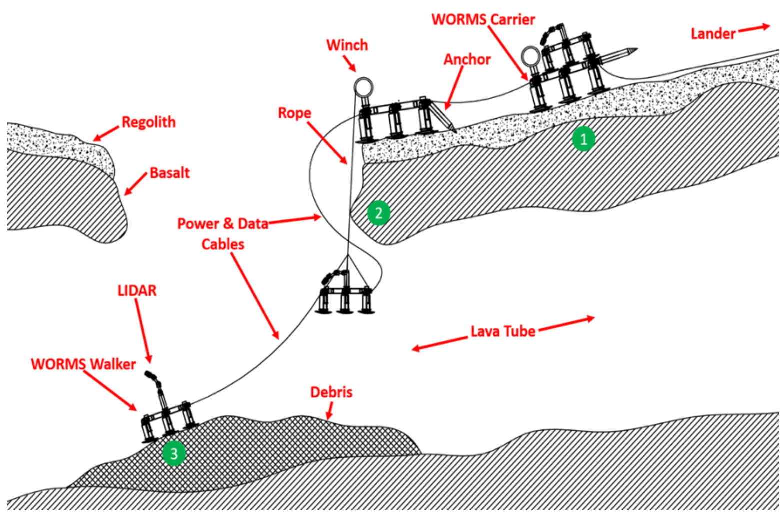


Figure 25 Exploring Lava Tubes Using Pairs of Worms

WORMS' long-term impact on NASA's lunar strategy lies in its potential to flexibly support various extreme terrain mobility missions throughout Artemis and beyond. New modular robots can be configured and deployed in the field, when the necessary software becomes available. Instead of sending a physical robot, NASA can send a new configuration with its code to a location which has WORMS parts in stock. New accessories, new worm species with different sizes and new functionalities can be developed as the need arises, such as supporting infrastructure development that requires heavy-duty surface mobility. Missions can fail gracefully because worms can be replaced in the field to complete the mission, and in general, hardware obsolescence will be reduced, saving taxpayer funds.

4 Verification testing on Earth

4.1 *Overview of Verification process.*

Verification summary statement: Our verification tests established the following findings at the system level:

- the elements of the architecture can be combined to form large, structurally rigid robot forms
- that six independent worms can coordinate to produce a walking gait,
- that six worms can share power.

We also established the following, at the subsystem level:

- the Battery Management Systems can reliably balance and charge the batteries
- our linchpin innovation, the Universal Interface Block (UIB), withstood higher static and dynamic loads than it would face on the Moon. Details are in the Verification Document.
- the shin, as designed with the two X crosses, also withstood high static and dynamic loads in testing. Details are in the Verification Document.
- The pallet structure has withstood (with visible deflections) all the nominal static and dynamic loads of walking, including high loads from fast-moving Worms during early testing of buggy code

Between the acceptance of the proposal and the midterm report, we decided to focus on only functional testing, and only TRL 4 as our target. We did not have sufficient resources to go directly from TRL 1 to TRL 5 in 7 months, and for this reason, we decided against carry out any lunar environmental testing. Instead, we invested our time and funding into materials, ~ two thousand hours of labor by paid undergraduate researchers, and to dissemination so we can receive feedback on WORMS.

Future verification testing: The remaining design development work is in two tracks. The first track has to do with additional functional testing to demonstrate more advanced capabilities:

Table 7 Remaining development tasks

Development Area	Development Task	Type
Walking	Walk over uneven terrain	Advanced functional
Species Module	Unspool power cable while walking (new module)	Advanced functional
UIB	To make it easier to decouple	Functional improvement
Pallet	Modify to reduce deflections	Improve safety

The second track has to do with preparation for TRL 5 / 6 testing:

Development Area	Development Task	Type
Redesign	Redesign the WORMS platform elements for the lunar environment: thermal, dust mitigation, radiation, and to allow room for specific flight-qualified equipment	Path to Flight

4.2 *Summary Table of Key Performance parameters*

Table 8 Key Performance parameters

KPI	Unit	MVP	Ideal	Scenario	Tech	Method	Measure
Endurance	m	300	500	Gen1, lunar gravity, no incline, no extra payload	Entire robot	Analysis	2404

Endurance	m	300	500	Gen1, lunar gravity, no incline, 400kg extra payload	Entire robot	Analysis	441
Endurance	m	300	500	Gen1, lunar gravity, Incline 30°, no extra payload	Entire robot	Analysis	495
Endurance	m	300	500	Gen1, lunar gravity, Incline 30°, 400kg extra payload	Entire robot	Analysis	91
Speed	m/s	0.1	0.15	Gen1, lunar gravity, no incline, 400kg extra payload	Entire robot	Analysis	0.143
Speed	m/s	0.1	0.15	Gen1, lunar gravity, incline 30°, no extra payload	Entire robot	Analysis	0.07
Speed	m/s	0.1	0.15	Gen1, lunar gravity, incline 30°, 400kg extra payload	Entire robot	Analysis	0.07
Min torque margin	%	35%	70%	Gen1, lunar gravity, no incline, 400kg extra payload, 0.143 m/s speed	Actuators	Analysis & Testing	61%
Min torque margin	%	35%	70%	Gen1, lunar gravity, 30° incline, 400kg extra payload, 0.07m/s speed	Actuators	Analysis & Testing	57%
Bending moment	Nm		<106	Bending moment on UIB with a load of 108Nm	UIB	Testing	108

4.3 Design Development Challenges and Mitigations

Table 9 Design Development Challenges and Mitigations

Challenge	Challenge Description	Mitigation Plan	Results
Safe testing of new software	New software could command unexpected movements, which present hazards to teammates or damage critical hardware	We suspended the WORMS-1 robot using a 1-ton gantry and clamped the robot to a rigid welding table. The robot could then walk "on air" to demonstrate the legs' motions.	The robot was supported during air walking tests. When sudden, unexpected leg movements occurred, the robot remained safely attached to the table without damage or incident.
Disarming the actuators in a contingency or emergency	Between tests, teammates may need to approach the robot to make adjustments or repairs. The robot's actuators should be disarmed so that teammates can safely approach the robot.	We used an E-stop that, when pressed, would activate relays that opened the actuators' power circuit in all legs.	The E-stop system opened the actuator power circuit when pressed.

Aligning the legs with the pallet	Manufacturing tolerance stackup led to misalignment between leg orientation and the pallet. The legs' actuators, especially the hips, should be aligned with the pallet to maximize useful torque output.	We machined slotted hip plates that allowed for +/- 4 degrees of hip axis adjustment.	The legs' hip actuators were aligned with the pallet to within 0.05 degrees.
Increasing actuator torque margin	In early calculations using fixed limb lengths, torque margins were too low for a 2-leg wave walking gait - and we had already committed to the actuators	We developed a new optimization tool that permitted simultaneous search over four parameters - two limb lengths, the hip swing angle and lateral distance from foot to pallet.	The tool recommended changed limb lengths and we obtained higher margins / speeds. Also, the robot survived all testing without incident, indicating that torque margins must have been positive.
CAN timeouts	In early tests, while sending commands to the actuators via CAN, we experienced inconsistent actuator communication.	We re-crimped loose actuator CAN cables.	We restored consistent CAN communication with the actuators.
Improving shin package accessibility	The Worm's shin was too small to package the Worm's electronics. Also, the shin's closed tube design was inaccessible.	We redesigned the shin to replace the walls with removable cross structures.	We opened the shin for easy electrical maintenance (replacing wires, probing with multimeter, etc.) while maintaining shin rigidity and strength.
Testing the neck Worm safely with E-stop	The neck Worm could collapse when the E-stop was pressed– cutting actuator power to all Worms. This risk would pose a hazard for teammates and damage the neck Worm or pallet.	We changed the neck from a Worm to a rigid post, made of the seventh Worm's structure.	The neck post supported the LIDAR during integrated tests without the hazard of a collapsing Worm. It also led us to realize that Species Modules can also be fitted to Accessories.
Power flow controller not passing qualification testing	The power flow controllers, which had four active switches (so 16 possible modes), were failing qualification tests.	We pivoted from an active power flow controller to a passive power sharing method.	The passive power sharing system successfully used battery power from all Worms to produce movement on one leg Worm.
End effector and UIB machining timeline	We machined a prototype end effector mechanical interface. We discovered that with our manufacturing resources and skill, it was infeasible for us to machine 28 of these interfaces.	We outsourced manufacturing of these end effector and UIB interfaces.	We received the outsourced end effectors and UIBs in time to structurally test the interface and perform integrated tests.

4.4 *Testing facilities*

Given our objective, which was to complete functional testing (to TRL 4) on a very complex system so as to demonstrate coordinated walking, our strategy for the testing facilities and setups was to create an environment for productive and safe testing. Therefore, we sought to control a number of well-established variables which weren't really being tested and which could have confounded our tests and experiments, so that we would hopefully observe only the effects of any weaknesses in the innovative systems we had designed and built.

Table 10 Testing facilities or setups used [12]

Category	Testing facility or setup	Examples of tests	Realism / DSNE
Structural – subsystems	Applying loads to clamped prototypes of mechanical subsystems	Bending moment tests on UIB; shear tests on shins	Potentially high, but need to consider effect of lunar environment on the material that was tested
Electrical – subsystems	Emergency Stop setup with two-stage key+button and relays	For safety, we used a setup where hitting a panic button at the desk 8 feet away from the robot would instantly cut power to all 18 motors	Low, but necessary for safe and productive testing
Software – subsystems	High-reliability router	Instead of radio, we used a highly reliable wired router to communicate with the embedded computers, to eliminate a potential source of errors when debugging our complex system	Low, but necessary for safe and productive testing
Integrated – system level	Gantry + welding table to restrain robot above ground	In order to allow the software team to quickly test their code in the hardware and accelerate the development cycle, we created a setup for "safe hardware-in-the-loop testing" where the legs were suspended above ground	Low, but necessary for safe and productive testing

4.5 *Alignment of Testing Plan with Lunar Environment*

Table 11 Alignment of testing plan with lunar environment

Aspect of lunar environment	Considered in testing?	Why or why not?
Reduced gravity	Yes	To model performance, size robot, estimate endurance
Radiation	No	COTS components will be replaced with rad-hardened ones
Rugged terrain	No	Out of scope for now due to very large volume of work to mature from TRL 1 to TRL 4; target for Nov 22 was to demonstrate the simplest kind of walking, on lab floor. The next step in our project is to adapt our walking gait to handle unstructured terrain.
Highly porous terrain	Yes	Tested alternative shoe designs in artificial snow
Abrasive regolith	No	Out of scope for now due to very large volume of work to mature from TRL 1 to TRL 4; iteration will be required
High slopes	Yes	To model performance and size robot
Temperature ranges	No	Out of scope for now due to very large volume of work to mature from TRL 1 to TRL 4; iteration will be required

Power Resources	Yes	Our chosen concept / use case unspools a power cable and sets up a recharging station

4.6 Future Work

The most important next tests are to demonstrate walking in uneven terrain and to investigate the effects of abrasive regolith on the system so as to plan mitigations and implement any design tweaks. Given that we started from TRL 1, we did not have the resources to complete these tests in the ~7-8 months between receiving funding and the Forum. However, there is interest at MIT to continue this project, so we hope to make progress on this front.

5 Safety plan and protocols followed

5.1 General Safety Overview

5.1.1 Facilities

⇒ The primary facility that will be used for building and testing will be **37-084 (both rooms)**.
One room will be used by the Lunar tower team, and one by the WORMS team.
⇒ TWO OR MORE MEMBERS MUST BE PRESENT AT ALL TIMES WHEN WORKING IN 37-084; WORKING ALONE IS NOT PERMITTED.
⇒ No food or drink allowed in 37-084.
⇒ The machine shop down the hall, The Deep, and two machine shops upstairs, Makerworks and LMP, will likely be used when machinery or advanced tooling is needed.
⇒ Each team member shall be made aware of the plans for the Lunar tower team as well, as they may pose additional safety hazards in the shared workspace.
⇒ Each team member shall be made aware that the nearest fire alarm pull station is outside the cage and around the corner of the hallway.

5.1.2 Personal Protective Equipment (PPE)

⇒ Closed-toed shoes and safety glasses will be worn when working in 37-084.
⇒ Nitrile gloves are required when handling any adhesives.
⇒ Hearing protection will be worn when loud machinery is in use.
⇒ When in machine shops, PPE will be worn as required by each shop.

5.1.3 Advising Information

⇒ The team is advised by Professor Jeffrey Hoffman and co-advised by Professor Olivier de Weck, Professor David Trumper and Professor Sangbae Kim.

5.2 Task-Specific Safety Overview

Task	Potential Hazards	Controls	Location	Responsible Members
1. Using hand tools (hacksaws, hand drills, files, screwdrivers, hammers, etc.)	1.a. Physical injury from sharp edges, blades, drill bits, or heavy objects	. Make sure tool users are qualified to use hand tools i. Make sure tool users use required PPE ii. Avoid carelessness and do not work when tired v. Use the right tool for the task	37-084 The Deep Maker - works	All

2. Using power tools (power drills, sanders, soldering irons, etc.)	Physical injury from sharp edges, blades, drill bits, or heavy objects Physical injury from improper use Physical injury from fumes (such as from soldering) Potential chemical contamination from substances such as lead solder	Make sure tool users use required PPE Make sure tool users are qualified to use power tools i. Avoid carelessness and do not work when tired Use proper ventilation at all times i. Use proper PPE at all times Use Reduction of Harmful Substance (RoHS) compliant lead solder, or lead-free solder i. Wash hands after use of solder and avoid unnecessary contact with skin and face	37-084 The Deep Maker - works	All
3. Machining with lathe or other rotary tools	Long hair or loose clothing could get trapped by machine Large spinning discs/blades have the potential for extreme bodily harm Blades or workpieces being machined may shatter under high stress resulting in injury	3.a.i. Tie back hair and do not under any circumstances wear loose clothing/jewelry 3.b.i. Wear work gloves, goggles and any other necessary PPE 3.c.i. Wear work gloves, goggles and any precautionary PPE necessary	The Deep Maker - works	All
4. Using rapid prototyping technologies	4.a. Fumes and ultrafine particle emissions from melting plastics	4.a.i. Use proper ventilation at all times	The Deep Maker - works	All
5. Electrical safety	5.a. Fumes/fires that may result from electrical shorts 5.b. Static discharge	5.a.i. Double check power connections 5.b.i. Always be properly grounded when working with electronics	37-084	All
6. Lifting and back safety	6.a. Physical injury from lifting heavy or unwieldy objects	6.a.i. In case of large or heavy systems or equipment, use a cart or other form of safe transportation 6.a.ii. Always lift from the legs 6.a.iii. Never lift a large object with only one person	37-084 The Deep Maker - works	All

6 Path-To-Flight

6.1 Overview of Path to Flight

The most complex part in our architecture, and therefore the one most at risk on the Moon, is the Worm. We identify two primary articulation design changes needed for the lunar environment. The first is **dust mitigation.** There is precedent for actuators, especially the strain wave gearboxes, with dust and vacuum protection in the Apollo Lunar Rover Vehicle and Pioneer 10 and 11 satellites [13], [14]. There are high TRL integrated rotary actuators that can be integrated to the Worms design. The Gen 1 Worm also features several structural joints to simplify manufacturing. However, these joints increase the risk of dust ingress. In future Worm generations, limbs will be manufactured as single parts using more advanced machines, such as 3D printers or CNC mills. We would conduct seal testing by walking in lunar simulants, such as the BP-1 simulant used at Swamp Works [15].

Second, a Worm would require a **thermal management system** to operate in the lunar environment. The Worm's primary heat sources are its actuators; in the Earth demonstration, each actuator generates ~60W of heat on average. Additionally, the robot's electronics, especially its batteries, have a narrow operating temperature range. Thus, there is a need for thermal management components, such as radiation plates or heat patches, to dissipate unwanted heat or heat electronics, respectively. We would conduct thermal vacuum and thermal cycling testing to qualify these thermal management components.

6.2 Path to implementation on Lunar surface

6.2.1 System path to flight

Launch environment: the WORMS architectural elements must be made robust to vibrations and acoustics that are to be expected during launch.

6.2.2 Worms path to flight

Predicting Performance on the Moon: We used our model / trade study tool to form Gen1 Worm mechanical and gait requirements. The Worm's limb lengths must remain constant between walking on horizontal ground and up to 30 degree inclines; however, the gait's X and h parameters, which are controlled in software, can vary between incline cases. We iterated between coxa length (L) and thigh length (M), and the two software parameters of hip swing angle and perpendicular, horizontal distance of foot from the pallet until it became apparent that L = 0.25 m and a thigh length (M) of 0.22 m were associated with nondominated measures of to provide flexibility in X and h parameters in multiple incline cases. With the limb lengths fixed, we selected X and h parameters that yielded sufficient minimum actuator torque margin and walking speed, as summarized in Table 4. These parameters suggest the WORMS-1 robot can maintain 30% or more horizontal torque margin and achieve more than 0.1 m/s walking speed on horizontal ground, and that WORMS-1 will be capable of carrying a payload of 400kg on the Moon, nearly four times its own mass of 120kg.

Gravitational field: feed-forward and gains must be very well understood, both with hardware-in-the-loop and in physics based models, in order to tune the gains for the lunar gravitational field.

6.2.3 UIB path to flight

For the UIB to be launched for a mission, a vibration test would be needed to assess the structural performance of the UIB connection under repeated loading. Due to the time limitation, the structural test was only performed through five repeated cycles, which were far less than what would be needed for a 500 meters walk of the robot into the center of lunar PSR. Thus, further vibration tests would be needed to qualify this UIB design for a mission.

In addition, as mentioned above, the design of a motor actuated pin locking mechanism will be needed to realize the autonomous coupling-decoupling process of the interface; and as opposed to having the power and data cords going around the UIB connection, jaw-shape power and data connectors need to be designed to simplify the connection process.

6.2.4 Pallet path to flight

The pallet design for the lunar environment should include additional protective measures for electronics placed within the pallet, including thermal regulation elements, radiation and dust protection elements. A more robust fastening system should be employed that would withstand lunar dust and the range of temperature variations characteristic to the lunar environment.

6.2.5 Opportunities for continued concept development

A number of our team members wish to continue on the WORMS project, and MIT AeroAstro & our advisors are supportive as well. Our next targets are to improve the walking capability so that the robot can handle uneven terrain, to strengthen the pallet, and to start working on design changes for a TRL 5 WORMS system, especially dust mitigation and thermal management. In due course, once we complete these, it will be advantageous for the project to align with NASA needs & plans, and also to seek out collaborators and mentors from NASA and JPL for joint testing and development opportunities of the WORMS architecture.

7 Results/Conclusions

7.1 Summary statement

The verification testing is promising: our Worms were firmly assembled into a 120kg robot, they were able to coordinate with the base node, they shared power and they executed a walking gait successfully. Thus, the WORMS team has demonstrated a proof of concept of reconfigurable robots. To turn this into reconfigurable lunar robots is the next big step, and it starts with further developing the software capabilities towards the direction of robust walking over unstructured terrain. Our mentors advised us that this takes time and that there’s no shortcut.

7.2 Key Results

Result	What did we show?	What are some benefits?	What are some possible next steps?
A Reconfigurable Robot	Proof of concept of the entire robot walking, and analysis showing that it can carry 3-4 times its own mass on the Moon	It opens the door to continued development and to realizing the benefits of demonstrating a robotics platform on the Moon by 2026	A simulation environment and a low-code interpreter, to make it easy to test and develop new behaviors for worms
Demonstrated the UIB	Withstood punishing subsystem tests and integrated tests	Holds without fail, relatively easy to attach or remove	Redesign the UIB to make it easier (and foolproof) to decouple
Demonstrated the first species module	The Mapper species module can be snapped on to the robot	Opens the path to developing and building other species modules that confer specialized skills	Standardize the power and data interfaces for species modules
Shown simple power sharing	One worm drew power from the batteries of all six worms	Makes it possible to extend endurance by sacrificing payload for batteries	A better BMS and a simpler flow controller, with only one switch
The architecture itself is a result / deliverable	Range of modules, accessories	Three generations of Worms deliver added scalability and versatility	Thoughtful design of a large set of future accessories, species modules, Gen2/3, and the command API structure

7.3 Conclusions

Our team focused on taking WORMS, an ambitious technology that did not exist prior to November 2021, from TRL 1 to TRL 4 in less than one year. We feel that we have accomplished that goal. We have shown that reconfigurable robots are feasible, that the first proof-of-concept reconfigurable robot should be able to carry payloads 3 to 4 times its own mass on the Moon, and that the idea of a platform of reconfigurable robots may have value and potential for supporting human space exploration. We know that life support on the surfaces of other worlds will be hard, implying both a high demand for labor (to maintain life support systems) and constraints on supply of labor (capped by the capacity of the life support system). This implies that robots will play a key part in the future of human space exploration. We believe that WORMS, or something like WORMS, has the potential of improving the efficiency, versatility, longevity and reliability of the robotic systems that future residents of the Moon, Mars and beyond will be relying on for their well-being.

8 Timeline

<table>
<tr><th rowspan="2">Project Week #</th><th rowspan="2">Week Start Date</th><th colspan="4">Weekly Actual Activities by Area</th></tr>
<tr><th>Mechanical Work</th><th>Electrical Work</th><th>Software</th><th>Integration, Testing and PM</th></tr>
<tr><td>18</td><td>5/23/2022</td><td>Complete designs</td><td rowspan="2">PCB layout</td><td rowspan="2">Leg kinematics in simulator</td><td>Procuring parts</td></tr>
<tr><td>19</td><td>5/30/2022</td><td>Procuring parts</td><td>Revising test plan</td></tr>
<tr><td colspan="6">Start of WORMS summer Undergraduate Research Opportunity Program (UROP)</td></tr>
<tr><td>20</td><td>6/6/2022</td><td rowspan="4">Fabricate limbs, outsource UIB / EE to Xometry</td><td>PCB layout</td><td rowspan="2">Leg kinematics in simulator</td><td>H&S trainings</td></tr>
<tr><td>21</td><td>6/13/2022</td><td>BMS testing</td><td>Finalizing ICD's</td></tr>
<tr><td>22</td><td>6/20/2022</td><td>Flow control tests</td><td rowspan="4">Two-leg kinematics in simulator - failed</td><td>Subsystem V&V</td></tr>
<tr><td>23</td><td>6/27/2022</td><td>Power sys int tests</td><td>Interfaces V&V</td></tr>
<tr><td>24</td><td>7/4/2022</td><td rowspan="3">Integrate worms</td><td>Design revisions</td><td>Supporting testing</td></tr>
<tr><td>25</td><td>7/11/2022</td><td>Procuring parts</td><td rowspan="2">Pallet and gait</td></tr>
<tr><td>26</td><td>7/18/2022</td><td rowspan="4">Wire batteries and BMS

Flow controller tests - unsuccessful</td><td rowspan="2">Gait redesign - "Magic Carpet"</td></tr>
<tr><td>27</td><td>7/25/2022</td><td>Limbs rework</td><td>Validation</td></tr>
<tr><td>28</td><td>8/1/2022</td><td>Integrate worms</td><td rowspan="2">Procuring new CAN controllers</td><td rowspan="3">Supporting int. testing</td></tr>
<tr><td>29</td><td>8/8/2022</td><td>Fabricate pallet</td></tr>
<tr><td>30</td><td>8/15/2022</td><td>Setup Gantry Crane</td><td rowspan="3">Build harnesses</td><td rowspan="3">Gait implementation - "Magic Carpet"</td></tr>
<tr><td>31</td><td>8/22/2022</td><td rowspan="2">Limbs rework to align hip joints</td><td rowspan="2">Procuring parts</td></tr>
<tr><td>32</td><td>8/29/2022</td></tr>
<tr><td colspan="6">Members who were away for summer return to campus</td></tr>
<tr><td>33</td><td>9/5/2022</td><td rowspan="5">Limbs rework to align hip joints, fabricate shoes</td><td>Pallet Main Power Bus</td><td>Integrated tests - CANBus control</td><td rowspan="7">Management of integrated tests: planning new tests in light of results, and coordinating all teams from week to week</td></tr>
<tr><td>34</td><td>9/12/2022</td><td>Connectivity and voltage tests - pallets and worms</td><td>Gait testing with one worm</td></tr>
<tr><td>35</td><td>9/19/2022</td><td>Debugging e-Stop</td><td>Gait debugging</td></tr>
<tr><td>36</td><td>9/26/2022</td><td>Step-down tests</td><td rowspan="2">CAN and encoder tests, found library bug</td></tr>
<tr><td>37</td><td>10/3/2022</td><td>Rebuild e-Stop using relays</td></tr>
<tr><td>38</td><td>10/10/2022</td><td>Alignment tests</td><td>BMS integrated test</td><td>Four-leg airwalks</td></tr>
<tr><td>39</td><td>10/17/2022</td><td>Schedule Margin</td><td>Power sharing test</td><td>Six-leg walking</td></tr>
<tr><td>40</td><td>10/24/2022</td><td></td><td></td><td></td><td></td></tr>
</table>

Type key: Design / SE | Procurement | Development | Testing | Schedule margin

9 Budget

WORMS Budget vs Actuals to date 10/23/2022

Line item	Cost driver	Spent	Committed	Total Spent or Committed	
ProCard purchases - Cost Object 1		$ 27,417.02		$ 27,417.02	
ProCard purchases - Cost Object 2		$ 8,530.56		$ 8,530.56	
ProCard purchases - Cost Object 3		$ 5,594.52	$1,260.00	$ 6,854.52	
B2P Purchases		$ 56,379.44		$ 56,379.44	
Subtotal Materials					$ 99,181.54
UROP - Steven Reyes S22 (11 wks, 40hrs/wk, $18/hr)	440	$ 6,480.00		$ 6,480.00	
UROP - Hanfei Cui S22 (6 wks, 20hrs/wk, $15/hr)	119	$ 1,785.00		$ 1,785.00	
UROP - Jessica Rutledge F22 (12 weeks, 10hrs/wk, $1	120	$ 1,800.00		$ 1,800.00	
UROP - Cesar Meza F22 (12 weeks, 10hrs/wk, $15/hr	120	$ 1,800.00		$ 1,800.00	
Subtotal Labor					$ 11,865.00
Overhead Phase I			$ 7,443.30	$ 7,443.30	
Overhead Phase II (reduced thanks to "fabricated equipment")			$ 300.00	$ 300.00	
Subtotal Overhead					$ 7,743.30
Total Spent or Committed to 9/21/2022					**$ 118,789.84**

Budget Major Line Item	Budget Phase 1	Budget Phase 2	Spent or Committed Phase 1	Spent or Committed Phase 2	Budget Total	% spent
Funds from BIG Idea						
Direct Labor (3 UROPs)	$ 12,510	$ 14,040	$ 11,865.00		$ 26,550	45%
Travel (ASCEND, BIG Idea, IEEE Aerospace)	$ -	$ 19,250	$ 26,257		$ 19,250	136%
Overhead	$ 7,443	$ 5,509	$ 7,443.30	$ 300	$ 12,952	60%
Testing	$ -	$ 20,000	$ -	$ -	$ 20,000	0%
Materials, Services + Misc	$ 61,923	$ 34,121	$ 7,181.54	$ 92,000	$ 96,044	103%
			$ 52,747	**$ 92,300**	**$ 174,796**	
Remaining BIG Idea funds available to spend as at 10/23/2022					**$ 29,749**	

Funds from MIT, Space Grant and David Shapiro Fund	MIT	Space Grant	David Shapiro Fund	
Jessica Rutledge, SG Fellow S22		$ 4,500		
Cesar Meza, SG Fellow S22	$ 1,000	$ 3,000	$ 2,900	
Fatema Zaman, SG Fellow S22		$ 6,000		
Cynthia Cao, UROP S22	$ 1,000		$ 2,900	
Tomas Cantu, UROP F22	$ 1,800			
Katherina Sapozhnikov, SG Fellow F22		$ 2,500		
Diego Rivero, SG Fellow F22		$ 2,500		
Anna Mokkapati, SG Fellow F22		$ 2,500		
Jacob Rodriguez, SG Fellow F22		$ 2,500		
MIT UA Travel stipends to Forum for eight undergraduates	$ 8,000			
	$ 11,800	**$ 19,000**	**$ 5,800**	
Total received and spent from other sources				**$ 36,600**

Total spent on project as at 10/23/2022	**$ 181,647**
Total funds remaining to spend on continued development of Gen2 of WORMS	**$ 29,749**

10 Acknowledgments

The team thanks the National Institute of Aerospace for organizing NASA's 2022 BIG Idea Challenge and the WORMS project's funding sponsors: NASA's Space Technology Mission Directorate / Game Changing Development Program; NASA's National Space Grant College and Fellowship Program; the Massachusetts Institute of Technology; and the Massachusetts Space Grant. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. 2141064 and by the Fannie and John Hertz Foundation. The team thanks Aleks Siemenn, Hanfei Cui, Isabella Golemme, Jolie Bercow, Juan Salazar, Stephanie Howe, and Zeyad Al Awwad for their design contributions, and Stephanie Sjoblom, Koji Takahashi, Duncan Miller and John Beilstein for supporting our preparations for the presentation and technology demo. We would also like to expresses our deep gratitude to our industry partners Boston Dynamics, MassRobotics and Robots5, for their mentorship and advice.

11 Appendix I – Three Generations of WORMS

	Gen 1	**Gen 2**	**Gen 3**
Single worm mass	10 kg	20 kg	60 kg
Max continuous torque	48 Nm	57 Nm	126 Nm
Worm length	~1 m	~1 m	~1.5 m
Lunar hexapod payload capacity	**~400 kg**	**~900 kg**	**~1.9 tons**
Power system and power sharing among worms	5Ah battery per Worm. Natural dynamics, all batteries operate as one large battery.	10Ah battery per Worm. Active power controllers provide operational flexibility and additional control & troubleshooting options.	30Ah battery per Worm, with upgraded active power controllers
Mobility	3 DOF per worm, as shown for WORMS-1 prototype	4 DOF per worm: add capability to rotate the end effector	5/6 DOF: add capability to tip or tilt the end effector(s)
End Effectors	Androgynous, with simple spring-loaded locking pins that require a five-piece custom tool and a lab environment to disconnect	Androgynous, same form factor as Gen1, with a fully redesigned manual locking system that can be disconnected in the field by a gloved, suited astronaut	Androgynous, larger form factor than Gen1 / Gen2, with autonomous connection and disconnection
Selection of Accessories	Apollo-style shoes, and a hexapod pallet (body)	Add: different types of shoes, cable spools, various types of pallets and large enclosed containers	Add: panels with end effectors for permanent installation on large tons-class payloads
Worm Specialization	All worms are identical, except for one modified by a pathfinder "Navigator" species module (LiDAR)	Species module mounting, power and data interfaces; proof of concept species modules for drilling, winching, charging, additional battery storage	Add: species modules with wheels and fluid transfer capability.
Inter-worm communication	ROS2 messaging over wired network using COTS embedded computers	ROS2 messaging over wireless network using industrial grade embedded computers.	Resilient ROS2 messaging over a double-fault tolerant wireless mesh network.
Worm Sensor Suite	Actuator Encoders, Power metrics	Add: RFID, IMU, Accelerometer, Load cell	Add: Engineering cameras and LED at tips of all end effectors.
Walking Gait	Coordinated execution of the Magic Carpet Gait on flat level ground with simple LIDAR object avoidance.	Coordinated execution of the Magic Carpet Gait on unstructured, level or inclined terrain, with localization and guidance map generation and dynamic planning.	Coordinated execution of a dynamic Magic Carpet Gait on porous lunar regolith with localization and guidance map generation and dynamic planning.

	Gen 1		Gen 2		Gen 3	
	Horizontal	30 deg Incline	Horizontal	30 deg Incline	Horizontal	30 deg Incline
Minimum Continuous Torque Margin	61%	57%	36%	35%	35%	31%
Forward Walking Speed [m/s]	0.143	0.070	0.069	0.025	0.054	0.012
Endurance [m]	438	91	388	51	1076	121
Hexapod Payload Capacity [kg]	~400		~900		~1900	
Robot Mass [kg per worm]	10.1		20.4		58.6	
Robot Packed Volume [m^3]	0.82					

12 References

[1] NASA, “NASA’s Plan for Sustained Lunar Exploration and Development.” 2020. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf

[2] G. C. Lordos *et al.*, “WORMS: Field-Reconfigurable Robots for Extreme Lunar Terrain,” in *IEEE Aerospace 2023*, Big Sky, Montana & Online. Submitted for Publication.

[3] NASA, “NASA’s Lunar Exploration Program Overview.” 2020. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

[4] H. Grant H., V. David T., and F. Bevan M., *Lunar Sourcebook: A User’s Guide to the Moon*. Cambridge University Press, 1991. [Online]. Available: https://www.lpi.usra.edu/publications/books/lunar_sourcebook/pdf/LunarSourceBook.pdf

[5] G. C. Lordos *et al.*, “WORMS: A Reconfigurable Robotic Mobility System for Extreme Lunar Terrain,” in *ASCEND 2022*, Las Vegas, Nevada & Online, Oct. 2022. doi: 10.2514/6.2022-4395.

[6] M. Martone, “Design and Control of a Large Modular Robot Hexapod,” Carnegie Mellon University, 2019. [Online]. Available: https://www.ri.cmu.edu/app/uploads/2019/12/Martone_MSR_Thesis.pdf

[7] Harmonic Drive, “Specifications of the flat and hollow shaft servo actuator.” 2011. [Online]. Available: https://www.harmonicdrive.net/_hd/content/documents/SHA25_32_SG_LV_Specification.pdf

[8] Rozum Robotics, “Servomotors.” [Online]. Available: https://rozum.com/documentation/servomotors/rdrive-85/datasheet/

[9] “AK80-64_AK Series Dynamical Modular_Exoskeleton Robot_CubeMars - Professional and Reliable manufacturer for robot actuators and frameless motors.” https://store.cubemars.com/goods.php?id=1143
[10] K. Damadeo, “NASA, Industry Mature Vertical Solar Arrays for Lunar Surface,” *NASA*, Mar. 23, 2021. http://www.nasa.gov/feature/nasa-industry-to-mature-vertical-solar-array-technologies-for-lunar-surface
[11] S. Potter, “Three Companies to Help NASA Advance Solar Array Technology for Moon,” *NASA*, Aug. 23, 2022. http://www.nasa.gov/press-release/three-companies-to-help-nasa-advance-solar-array-technology-for-moon
[12] NASA, “CROSS-PROGRAM DESIGN SPECIFICATION FOR NATURAL ENVIRONMENTS (DSNE).” 2020. [Online]. Available: http://bigidea.nianet.org/wp-content/uploads/SLS-SPEC-159-Cross-Program-Design-Specification-for-Natural-Environments-DSNE-REVISION-H.pdf
[13] K. Ueura and D. R. Slatter, “DEVELOPMENT OF THE HARMONIC DRIVE GEAR FOR SPACE APPLICATIONS,” p. 6.
[14] I. Schafer *et al.*, “Space lubrication and performance of harmonic drive gears,” vol. 591, pp. 65–72, Jul. 2005.
[15] R. P. Mueller, J. G. Mantovani, and L. Sibille, “Geotechnical Properties of BP-1 Lunar Regolith Simulant.” 2019. [Online]. Available: https://www.hou.usra.edu/meetings/lunarisru2019/presentations/5068_Mueller.pdf