WORMS: A Reconfigurable Robotic Mobility System for Extreme Lunar Terrain

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The Artemis Base Camp phase of NASA's planned return to the Moon will feature extensive exploration and infrastructure development needs in and around extreme lunar terrain such as permanently shadowed regions (PSRs), lava tubes, cliffs and inclines, and highly porous regolith. In view of this, NASA and its partners are likely to have substantial, expanding, evolving and diverse needs for extreme terrain robotic mobility support in the years to come. In addition, there will be a long-term need for robots to support many types of infrastructure development tasks, in all types of terrains. The Walking Oligomeric Robotic

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Mobility System (WORMS) presented here is one of seven finalists to NASA's 2022 BIG Idea Challenge which focuses on extreme lunar terrain access. WORMS refers to an architecture where a robotic mobility capability emerges from the field-reconfigurable integration of a small set of articulating worm-like robots with simple accessories such as shoes, pallets, spools, and containers. In addition, modular plug-in "species modules" can modify the Worm's end effector and infuse specialized capabilities to specific Worm robots. The key enabling technologies are three: a Universal Interface Block (UIB), which enables easy assembly and disassembly of robots; a power sharing scheme, so that all batteries in a robot configuration are available to its hardest-working Worm element; and software, that enables Worm-to-Worm coordination. The vision is that, as long as a configuration profile exists in the code library and the necessary Worms, accessories and species modules are at hand, any library robot configuration should be possible to assemble on the Moon by a non-specialist in a matter of minutes or hours and assigned to its task. Further, the oligomeric (few types of parts) aspect of the architecture means that if a robot suffers damage, the damaged Worm or accessory can be swapped out in the field with a replacement part so that the robot can continue its mission with minimal disruption. Overall, the platform is intended to enable Artemis Base Camp crews to keep a stock of Worms, accessories and species modules with which they can configure robots as needed and task them to various missions in support of their exploration and development goals. WORMS-1, a proof of concept of the first generation, has been built, and two more generations are planned, each adding more capabilities and scale to the architecture. With each generation the potential use cases and applications multiply; five sample use cases are presented in the paper. The WORMS architecture feeds 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. Our approach is such that WORMS can be a mass-producible, reconfigurable, reusable and scalable system, to better support a range of extreme access needs and various lunar infrastructure development scenarios. The architecture is intended to be resilient, versatile, easily maintainable, low-cost, evolvable, flexible and future-proof.

I. Introduction

With the Artemis program, the National Aeronautics and Space Administration (NASA) is planning to restart human exploration of the surface of the Moon. Unlike Apollo, Artemis is intended to be the beginning of a lasting, evolving and expanding presence on the Moon, not only for NASA with its planned Artemis Base Camp, but also for its commercial and international partners. As of this writing, 20 nations have signed the Artemis Accords [1] in anticipation of an era of shared exploration of the Moon. The Lunar Surface Innovation Consortium [2], launched at the start of the Covid-19 pandemic, is a forum for the investigation of all aspects of what will be needed for lunar surface operations, and has already grown into an active community of hundreds of entrepreneurs, academics and NASA engineers. Meanwhile, SpaceX is developing a new lunar lander for NASA [3], new lunar surface solar and nuclear power systems are in development [4,5], as well as new space suits [6], new rovers [7,8], and even lunar cellphone service [9].

To establish this lasting presence at the lunar south pole, NASA is developing new landing capabilities to the moon through the Human Landing System (HLS) Program [10]. NASA is also incorporating industry through the Commercial Lunar Payload Services (CLPS) Program [11] to increase landing capacity for science and exploration robotic payloads. These programs will help transport more payload mass to the lunar surface; however, before astronauts reach the moon, robotic systems will be needed to transport many different payloads from lunar landers through and into difficult-to-reach destinations. Before and after the Artemis III human landing mission, there will be a need for various robotic exploration and prospecting rovers, for infrastructure such as vertical solar panel arrays and surface fission power reactors, for in-situ resource utilization (ISRU) experiments and more. All these must be deployed, powered, operated and maintained to advance our capabilities that will ultimately enable the envisioned Artemis Base Camp long-term lunar presence. Infrastructure such as roads, power and data networks and radiation-shielded living and working space will need to be constructed, robotically at first before humans return to the Moon. Once astronauts visit the surface, their time will be at a premium and robots will still be needed to augment exploration, deployment, development and maintenance tasks. The lunar South pole region, which is the destination of the Artemis program, with its Permanently Shadowed Regions (PSRs), ridges and sunlit peaks, pits, lava tubes, highly porous and highly inclined terrain, is especially challenging to explore and requires mobility solutions that do not involve wheels.

In view of the above, NASA and its commercial and international partners are likely to have substantial, evolving, diverse and growing needs for unconventional robotic mobility support on the surface of the Moon for years to come. Over time in the 2030's, amidst an expanding presence on the Moon by NASA and its international and commercial partners, mobile robots of many different types and sizes will be in demand. Absent holistic planning for all these needs, there will be a heightened risk of obsolescence due to evolution in the nature of missions, leading to incompatible sui generis systems, costly / difficult maintenance and hard-to-sustain supply chains for spare parts.

Accordingly, in our investigations, we strove for a novel platform architecture that aims to not only meet the technical requirements of early Artemis-era missions, but also to rise to the challenge of these programmatic risks over the longer term, through Artemis Base Camp and beyond. Ultimately, we explored the design space for lunar robotic architectures in search of a modular, mass-producible, reconfigurable, reusable and scalable family of robots. The vision is to have a robotic platform architecture that could potentially meet needs for robotic services and be of value to several future lunar extreme terrain access and lunar infrastructure deployment and maintenance use cases.

II. Literature Review and Problem Statement

As shown in Figure 1, the lunar surface has many areas that can be classified as extreme terrain and that require novel mobility solutions.

A. *Lava tubes, caves, pits* - NASA's Lunar Reconnaissance Orbiter (LRO) found over 200 pits in the moon of which 16 are believed to be collapsed lunar pits. Lava tubes have been studied as possible locations [12–14] for emplacing habitats which can be made safe from radiation, micrometeoroids and which have more stable temperatures throughout the lunar day and night.

B. *Permanently Shadowed Regions (PSRs)* - lunar polar cold caps within shadowed regions can trap volatiles from external sources such as comets or asteroids for a long time [15]. PSRs are of interest to both scientists and human explorers because they are expected to preserve water ice and other frozen volatiles that have accumulated over eons [16–18]. These resources could be integral to sustainable exploration of the Moon and to future habitation.

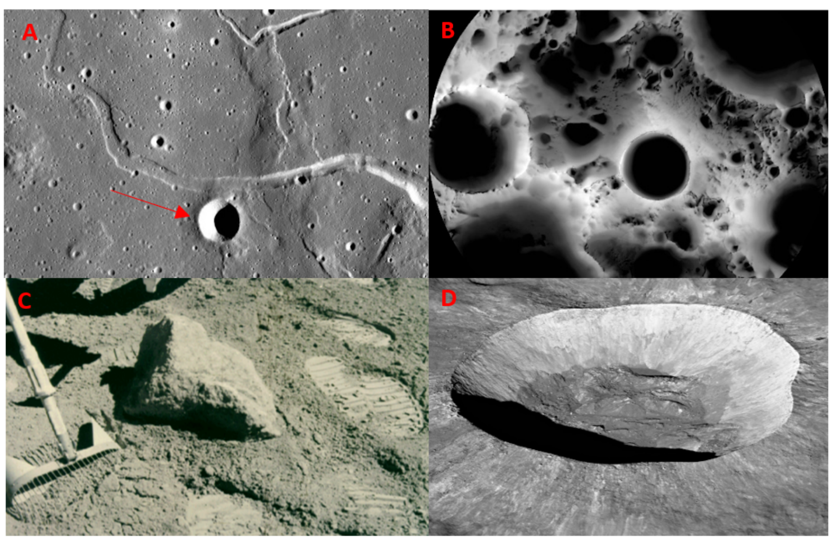

Fig. 1 A) Lava Tubes, Caves and Pits; B) Permanently Shadowed Regions; C) High Porosity Regolith; D) Steep and Uneven Terrain. Images credit: NASA

C. *High porosity regolith* - lunar regolith covers nearly the entire lunar surface, but there are many regions where the regolith thickness can reach 15m in depth [19]. For instance, the highlands in the lunar South Pole have an average regolith thickness of 10-15m in depth. The South Pole is of special interest to scientists as there are many PSRs located there which may have remnants of volatiles such as hydrogen and water ice. The capability of traversing high porosity regolith is therefore an essential advancement for further lunar exploration.

D. *Steep and Uneven Terrain* - the moon has many topological features, including craters and mountains (massifs). Exploring the craters are of particular interest because they provide a fundamental understanding of the Moon's history and also may contain valuable resources such as water ice. Previous lunar expeditions have already found evidence of water and hydrogen in lunar craters [20]. It is important to continue exploring these features to gauge the type and availability of resources to advance future human exploration, however access is expected to be a challenge due to the steep or uneven terrain.

Given the limited mobility of astronauts and the harsh environments that exist on the moon, collaboration between humans and robotic mobility systems will be essential to support exploration activities. Most lunar mobility systems to date have been designed using a wheel-based architecture since they are naturally easier to control and have been proven to work reliably here on earth. All 7 rovers that have landed and operated on the lunar surface to date have implemented a wheeled drivetrain.

After Apollo 11, the first of these wheeled explorers was the autonomous rover Lunokhod 1, designed by the Soviet Lavochkin design bureau, which landed on the moon in 1970. This was the first autonomous rover to ever be sent outside of Earth's atmosphere and was driven by 8 rigid spoked wheels with a wire mesh rim connected to three hoops traversing the circumference. Weighing in at 756kg, Lunokhod 1 was capable of traversing slopes up to 32 degrees and covered a total distance of 10.54 km. A slightly larger Lunokhod 2 was launched 3 years later [21].

In between the launches of the two Lunokhod rovers, the Lunar Roving Vehicle (LRV) was developed by Boeing for Apollo 15, 16, and 17. The 4-wheeled rover included 2 seats to assist with human mobility and had a mass of 210kg with an additional 490kg payload. The frame was 3.1x2.3x1.14m and each wheel had its own electric drive that could be decoupled for steering. Initially, the rover experienced challenges with adverse lunar dust effects [22].

Yutu, a 6-wheeled solar powered rover, was developed by the China Academy of Space Technology for Chang'e 3 in 2013. Weighing 120kg and spanning 1.5m tall with 20kg payload of instruments, the vehicle was the first robotic rover to successfully traverse the lunar surface since Lunokhod 2. It included instruments such as a stereo camera and ground penetrating radar. Yutu continued to transmit data from the lunar surface until Dec 2016 [23].

Pragyan, built by the Indian Space Research Organization (ISRO) as part of the Chandrayaan 2 mission, was a 6-wheeled vehicle weighing 27 kg and ran on solar power. It deployed from the Vikram Lander and traveled at 1cm/s. The rover also included navigation cameras and experiments with X-ray detection [24].

Although these systems achieved their intended missions using wheeled mobility systems, that does not mean they did so without difficulty. A briefing study performed by Dr. David Kring, principal scientist at the Lunar and Planetary Institute (LPI), brought out multiple faults experienced by Apollo-era wheeled rovers. Past rovers were all wheeled vehicles and encountered a variety of issues, such as limited or no mobility in soft soil, wheel sinkage, or limited trafficable slopes [25].

In summary, lunar rovers to date have all been wheeled vehicles and encountered a variety of issues, such as limited or no mobility in high porosity regolith, wheel sinkage, and limited trafficability on highly inclined slopes. Although wheeled mobility systems have succeeded on relatively benign lunar surfaces, extreme lunar terrain such as lava tubes, caves, craters, cliffs, and high porosity regolith have been and remain out of bounds.

For the needs of the Artemis program, new surface mobility architectures beyond wheeled rovers will be required to access extreme terrain. However, many proposed lunar surface exploration systems are still using wheel-based drivetrains. For instance, Lockheed Martin has proposed a human operated un-pressurized vehicle similar to the Apollo-era LRV, and the Canadian Space Agency has been developing a "mobile lunar laboratory" which would be the first pressurized human transportation system on the moon. The need for these types of mobility systems is clear given the Live and Explore objectives articulated in NASA Space Technology Mission Directorate strategic framework [26]. However, these mobility systems will still be limited to relatively safe and flat terrain, so new surface mobility capabilities will be required for robotic and human access and operations in extreme lunar terrains.

As a result, there have been a variety of next-generation lunar rovers proposed by NASA that attempt to advance the existing wheeled architecture of previous systems. Most notably, NASA Ames is developing the "Volatiles Investigating Polar Exploration Rover" (VIPER) [27], which features increased maneuverability for extremely porous regolith by advancing direct drive control, wheel design, and omnidirectional mobility. This combined with real time teleoperated control will allow the rover to explore and analyze possible lunar ice deposits at the lunar poles.

Another technology development direction has been to keep wheel-based drivetrains while adding other functionality to them such as increased degrees of freedom, flexibility, and decreased size. An example is the "A-Puffer" [28], a 2 wheeled robotic system developed at JPL that can fold up to fit in tight crevices such as tunnels as lunar lava tubes.

Given the simplicity and low mass of smaller robotic systems, another design for lunar mobility is the deployment of multiple autonomous systems that work together to complete tasks such as exploration, mapping, and communication. A prime example using this framework for small robots specifically is NASA's Cooperative Autonomous Distributed Robotic Exploration (CADRE) project [29]. That team is developing small 4-wheel robots programmed to work as an autonomous team to explore the lunar surface, collect data, and map different areas of the Moon in 3D.

As small robots can only complete small tasks, another research direction has been towards resilient multi-agent autonomy systems. An example of this is the COSTAR/Nebula fleet [30], a team of robots tasked with exploring unknown hazardous urban and cave terrain, developed for the DARPA Subterranean Challenge. Employing diverse robotic mobility systems such as quadrupeds, tanks, drones, and standard wheeled systems, it allows for the traversal of dynamic environments when each respective robot is placed in the terrain for which it had been optimized.

In summary, there is a need for a robotic mobility system which can offer robust access across all lunar environments, including extreme terrain such as steep inclines, highly porous regolith, pits, lava tubes and permanently shadowed regions. This has not yet been achieved by any past or currently proposed lunar rover or robot architecture. NASA's 2022 BIG Idea Extreme Terrain Mobility Challenge [31] invited proposals to address one such type of terrain, and in October 2021 a team was formed at MIT to propose a technology that could meet this need.

III. High-level WORMS System Description and Development Roadmap

WORMS development was driven by four guiding principles: versatility and scalability of the concept; competitive applicability to a real, near-term operational scenario; and the feasibility of a first demonstration in the 2026 timeframe. Selecting a concept and developing a detailed architecture consistent with all of these principles has involved numerous strategic discussions, feedback sessions, and incremental steps.

A. Concept Selection Informed by Stakeholder and Mission Analysis

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The MIT WORMS team started the project with background research on the terrain near the lunar south pole of the Moon, in order to understand operational scenarios and future needs for robotic mobility, including but not limited to extreme terrain mobility. The team identified a number of potential operational scenarios, including geotechnical characterization of extreme terrain, 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.

With these problems identified, the team next brainstormed types of mobility and also animals that have evolved diverse mobility capabilities. Noting that animals adapted their mobility capabilities to their habitats, the team created several initial pairs of operational scenarios and robotic mobility concepts, such as a spider lowering a bug into a lava tube, a goat pulling an ox up a steep slope, or a penguin 'swimming' through highly porous regolith. At the down-selection stage, it became apparent that a modular architecture based on worm-like members would provide a capability for field-reconfigurable robots that could, subject to software availability, address operational scenarios in almost any extreme terrain, from traversing safely over high porosity regolith to winching down through a skylight into a lava tube. Thus, the creative and engineering process used led to the invention of the WORMS concept.

B. WORMS System Architecture

The WORMS modular elements are classified into three categories, these being *Worms*, *Species Modules* and *Accessories*. Worms provide articulation and load-bearing capability. Species modules can be used to infuse specialized capabilities to a Worm, while accessories meet specific functional needs, for example Shoes for walking, or a Pallet to carry payload and also to provide a body frame. A theoretically unlimited variety of diverse extreme mobility robots can be built by combining several Worms (and optionally, Species Modules) with one or more Accessories in different physical arrangements, and by providing software for their coordinated operation. A visual representation of this defining characteristic of WORMS architecture is provided in Fig. 2 below:

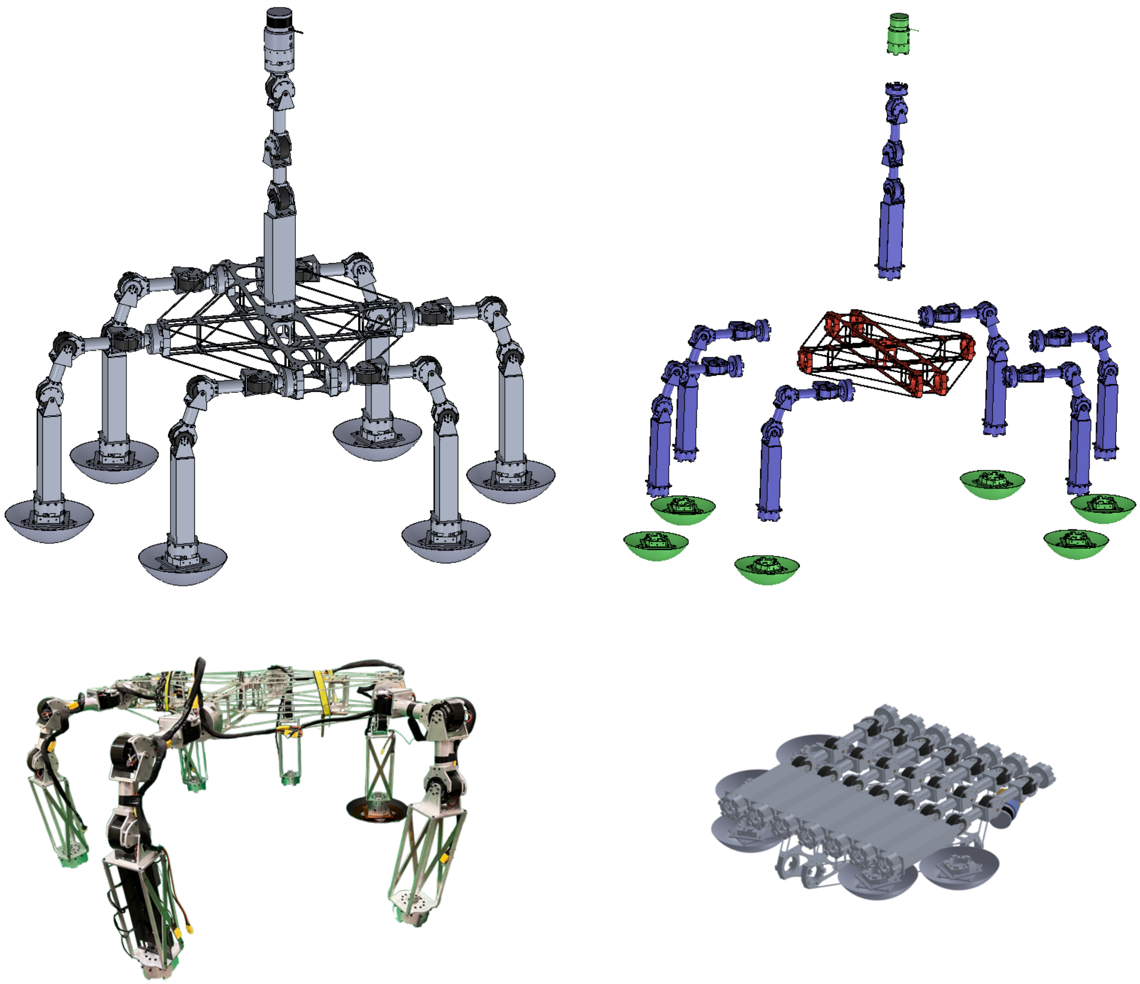

Fig. 2 Clockwise from top left: the WORMS-1 design for a mapping robot; an exploded view showing the Worms, accessories and species modules used to assemble WORMS-1; the required parts for this robot flat-packed into a volume of 1.4m x 1.65m x 0.35m (0.82 m^3); and a photo of the partially built WORMS-1 robot.

Individual Worms are intended to be identical in all respects: in our Generation 1 (Gen1) proof of concept, Worms can share electrical power, can communicate with each other for coordination purposes and have three joints in two perpendicular planes. Future generations of Worms are planned to have basic sensing capabilities, such as sensing loads, light, and accelerations, or seeing in stereo vision using their lighting.

Worms can be differentiated by interchangeable *Species Modules* which are located inside a volume provided in the end effector and which grants various special capabilities to that end of the Worm. For Gen1, as a proof of concept we have built a LIDAR species module to support mapping and navigation. For future generations of the architecture, a universal Species Module power & data connector will be developed to support the development of an ecosystem of interchangeable species modules, including the “Anchor” species which features a small drill to anchor a foot into the ground while walking, the “Endurance” species which provides additional battery capacity, the “Charger” species which exposes a charging port connector, and the “Winch” species featuring a high-torque motor, spool and steel cable for load-lifting applications. Hybrid Worm species are possible by using a different Species Module at each end.

Accessories are simple capability-enabling forms and can include *Pallets, Containers, Spools, Shoes* and more. Accessories support basic physical capabilities such as walking through a specific type of terrain, carrying a payload, or deploying a cable. For Gen1, we have developed a shoe which is a compromise for walking on either rocky or highly porous terrain, as well as a Pallet or robot body which serves the functions of providing a rigid body, a central power bus for power-sharing and a platform to carry payloads. Payload capacity is up to 400kg for our Gen1 proof of concept hexapod robot.

Emergent Mobility: The individual articulation capabilities of each individual Worm, integrated with Accessories and software, give rise to the emergent mobility of a WORMS robot. Software specific to each WORMS robot configuration ensures that every Worm is capable of coordinating with the other Worms that are part of the same robot to perform a variety of complex tasks such as: walking as a quadruped, hexapod, octapod or centipede; for unspooling a power cable while the WORMS robot is walking; for winching a heavy load into a lava tube skylight; or, for recharging the batteries of other robots. Each Worm's ability to communicate and coordinate with other Worms is leveraged by software which provides the identity and coordination to the WORMS robot, leading to the desired emergent mobility behavior and to the fulfillment of many conceivable mobility missions.

C. WORMS Technology Development Roadmap

The WORMS architecture is being developed through three Worm robot Generations, as outlined in Table 1. A proof-of-concept first generation (Gen1) robot consisting of 7 Worms, 7 shoes, 1 pallet and 1 LiDAR species module, weighing 110kg and standing as tall as a human, has already been built and is currently being tested at MIT.

Table 1 Roadmap of WORMS Technology Development

	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.

D. Overview of First Generation (Gen1)

Generation 1 Worms were used to assemble the proof of concept WORMS-1 hexapod and demonstrate key technologies: androgynous Universal Interface Blocks (UIB) end effectors, a minimal three-degree-of-freedom (3 DOF) articulation capability, sufficient inter-Worm communication protocols to support an emergent walking capability, developed on a ROS2 platform, and a basic power-sharing architecture. In addition, a pathfinder "Navigator" LiDAR species module has been included in Gen1, to inform the design of a universal interface scheme for a variety of species modules. Gen1 robots, shown in Fig. 3, are intended as a technology demonstration to de-risk all these key technologies and inform the development of a more capable Gen2 that can actually perform a variety of missions.

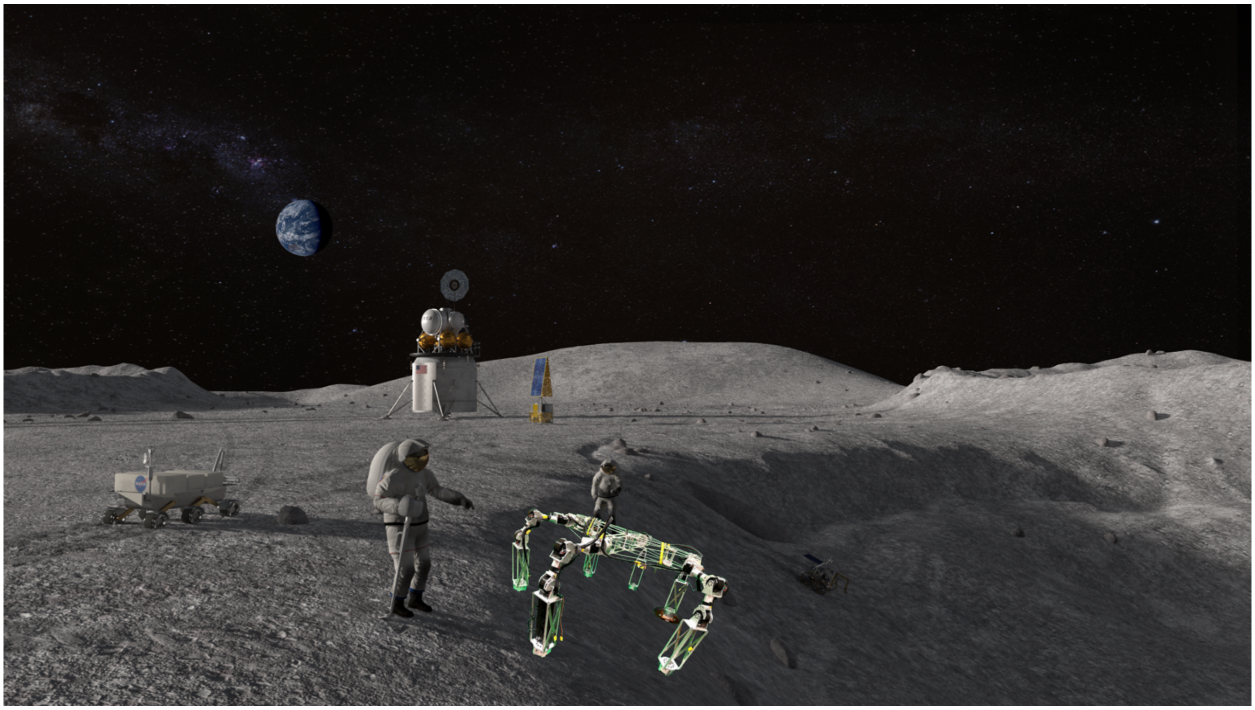

Fig. 3 A WORMS robot supporting crew operations in extreme lunar terrain

E. Overview of Second Generation (Gen2)

Generation 2 (Gen2) adds an additional degree of freedom, doubles the mass and payload capacity of WORMS robots, introduces a large range of accessories and species modules, adds active power distribution controls to provide extensive operational flexibility to crews and Mission Control, and standardizes the species module interface from both a power and communications perspective to increase the capabilities of the WORMS system.

Gen2 will incorporate new joint actuator selections which exploit the structure of the walking gait to save mass and power. Rotational actuators on end effectors can interface with accessories to allow for species module rotation. With a shaft interface, different accessories may have different gearings according to their speed and torque needs; for instance, shoes and winch units would need high torque, whereas navigation applications would prioritize speed. With the same limb lengths as the Gen1 Worm, the Gen2 Worm is primarily limited in torque at the knee actuators and in speed at the hip actuators. Different actuators can be selected for each joint such that higher speed, lower torque and lower speed, higher torque actuators are used on the hips and knees, respectively. Hip and knee actuators will incorporate brakes or another measure to allow the system to maintain a stationary position with minimal power consumption.

Gen2 also provides broad Species Module support for drills and other tools, extra compute power, radios, science instruments or additional batteries. Gen2 Worms would be enhanced with additional sensors such as load cells and IMU's, enabling more sophisticated motion control in more challenging environments. The embedded software provided with each Worm will include capabilities for real-time gait adaptation and obstacle avoidance.

F. Overview of Third Generation (Gen3)

The third-generation (Gen3) WORMS architecture focuses on scaling up to carry heavier payloads of the order of tons, on making the architecture more resilient, on rounding-out the WORMS feature set and on adding the capability for autonomous reconfiguration of a WORMS robot.

Gen3 would feature 1.5m long Worms with a larger diameter universal interface block. Mass, battery size and payload capacity would scale by a factor of ~6 relative to Gen 1, with a 60kg Worm. This mass and size scale was selected so that crews on the Moon will be able to manually carry, connect or disconnect one Worm from a robot assembly. Modeling with indicative mass distributions indicates that Gen3 payload capacity would approach 2 tons. To improve resilience and usability, Gen3 will feature integrated electrical and data connections that close and open simultaneously with the mechanical connections between Worms and accessories or species modules, eliminating external cables that could be damaged or exposed connectors that could be affected by lunar dust.

Gen3 will also take advantage of its higher mass budget to include a fifth degree of freedom allowing tipping or tilting of the hip joint, and incorporate redundancy in the power, data, and sensing subsystems, with resilient ROS2 messaging over a double-fault tolerant wireless mesh network. A custom structural battery would be designed to optimize the distribution of weight through the robot limbs. Advanced power-management capabilities such as the ability to electrically connect or disconnect a Worm on the moon regardless of charge level would be included in the Gen3 version.

Finally, image-recognition cameras, lighting and sensors will be added to all end effectors, enabling the capability for autonomous reconfiguration of a WORMS robot, by adding or removing Worms autonomously without human intervention. The range of accessories and species modules will be extended and updated: Gen3 will add pressurized gas and liquid tanks; a new series of species modules to handle gas and fluid transfers; and special panels with end effectors for permanent installation on large tons-class third-party payloads, so that WORMS legs can be attached to landers, habitats, tanks, power systems or ISRU units in order to relocate them through and to any terrain.

IV. Overview of WORMS-1 Proof of Concept Robot Build

The Generation 1 (Gen1) Worm's size was set by designing, building and testing a proof-of-concept robot assembled out of 7 Worms, 6 Shoes, 1 Pallet and 1 LiDAR Species Module. By varying the Worm's limb lengths, limb masses, and actuator masses to meet the proof-of-concept WORMS-1 system's performance goals: walking faster than 0.1m/s, traversing inclines steeper than 30degrees, and carrying payloads at least the WORMS-1 hexapod's mass in lunar gravity. To achieve this last goal in Earth gravity demonstrations, we reduce the payload mass by a factor of 6–the approximate ratio between Earth gravity and lunar gravity–such that the Worms' effort on Earth mimics that they would experience on the Moon with the payload mass goal. The Hexapod Actuator Calculator was used to achieve an initial closed design using an off-the-shelf actuator with more than 30% margin to the actuator's continuous torque rating [32]. For a 100kg-class hexapod with a 0.8m Worm length, we selected the T-MOTOR AK80-64 actuator–an integrated brushless motor and planetary gearbox–to provide a minimum 71% and 32% continuous torque margin for walking on horizontal ground and 30 degree inclines, respectively. The AK80-64 actuator has low mass (0.85kg), high continuous torque (48Nm), and moderate continuous torque speed (57rpm) at 48V [33]. Having designed a WORMS-1 hexapod that could be tested and demonstrated in Earth's gravity field, we prototyped the design and limb lengths of the Gen1 Worm robot. We also designed a 14" diameter shoe intended to be a compromise between uneven and highly porous terrain, supporting the hexapod both on rocks and on regolith.

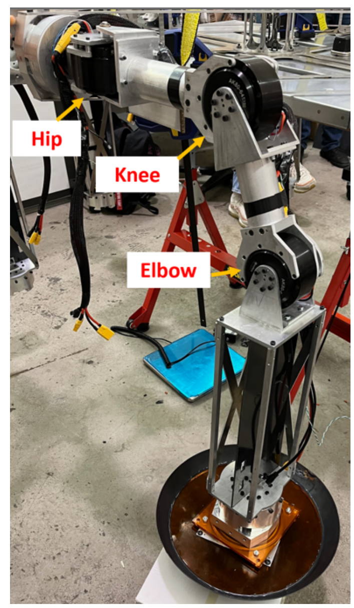

Fig. 4 A Gen1 Worm robot

With this configuration and walking parameters, the robot is capable of carrying a ~400kg payload on the Moon. Limb lengths and masses were further optimized using a custom actuator torque and speed model, which uses a novel hexapod gait that controls the horizontal distance between the pallet and the shoes. This optimization set the Gen1 Worm's mass and length–10kg and 1.1m length, respectively–and the WORMS-1 system's mass: 110kg. An assembled Gen1 Worm is shown in Figure 4.

A. WORMS-1 Worm Structure

The WORMS-1 robot's Worm structure is constructed primarily of Aluminum 6061 tubes and 6063 angle brackets. These materials were chosen for their relatively high strength to weight ratio, excellent machinability, and low cost. A static structural model was built using Excel and FEA to analyze the strength of the Worm structure in 2 primary load cases–horizontal and incline walking. A minimum yield safety factor of 3 was achieved. This high yield safety factor reduces the risk of structural failure during integrated tests. By validating the structural design model using data from WORMS-1 walking tests, the Worm's structural mass can be further optimized in subsequent Worm generations.

B. WORMS-1 End Effectors: Universal Interface Block

The Gen1 end effectors and UIBs, shown in Figure 5, demonstrate the androgynous mechanical connection needed to easily attach or remove Worms. This interface uses 5 jaws on each side to produce a rigid clamping action, which is locked using 5 spring loaded pins on each side. A wedge tool is used to compress each pin and remove the rotational constraint during disassembly. In Gen1, these interfaces are purely mechanical; power and data cables are connected separately from these end-effector and UIB interfaces. Therefore, this simplified mechanical interface has substantial room for further development in Gen2 and Gen3 to support removal by a gloved, suited astronaut in the field without the use of any specialized tools and to provide robust power and data connections as part of the interface.

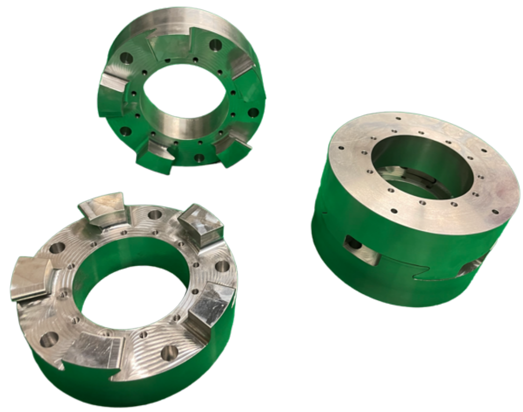

Fig. 5 Universal Interface Block (UIB)

C. WORMS-1 Accessories: Pallet and Shoes

The pallet, which acts as the payload structure connecting 7 Worms, is a sandwich structure made of 3mm thick Aluminum 6061 plates bonded by I-beam supports. Multiple iterations of the double-layered pallet structure in FEA reduced the mass from 15.50kg to 7.67kg, resulting in mass-efficient, sturdy pallet plates. To increase stability, the pallet utilizes the UIB housing structures as support in addition to the I-beams. The final plate geometry is a rounded, pocketed rhombus shape of size 1291x1000mm, as shown in Fig. 6. With a 121mm offset between pallet plates, the pallet achieves the high rigidity and strength required for the WORMS-1 robot, which generates large internal moments from 1.8m separation between opposing WORMS-1 shoes.

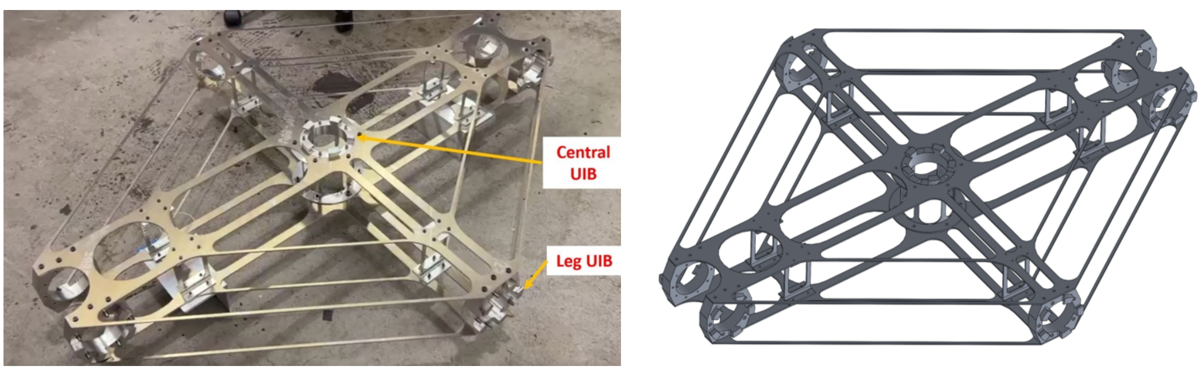

Fig. 6: Pallet prototype (L) and CAD drawing (R)

Three shoe designs, flat, rounded, and foldable, were pursued in parallel to maximize gait stability in varying lunar environments as well as minimize weight and space. As a load test, 14kg of weight was applied in the center of each shoe design over ~12cm thick artificial snow, mimicking the Worms applying a force on the shoe over high porosity lunar terrain. The flat shoe design displayed marginal sinking while the rounded wok saw significant sinking but stabilized before submerged. However, the flat shoe cannot accommodate treading on larger foreign objects or mis-angled gaits. The rounded shoe base shown in Fig. 7 was selected for its anticipated ability to support the WORMS-1 robot at all angles of impact and stabilize in uneven lunar terrain. This ability will be tested in ongoing integrated tests taking place at MIT this Fall.

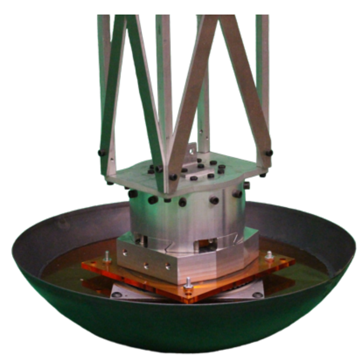

Fig. 7: Rounded shoe

D. WORMS-1 Power Distribution System

The WORMS-1 power distribution system is a scaled-back, simplified system used for proof-of-concept testing as the necessary electronics for advanced features are built and tested. Each Worm contains a single 6-cell lithium battery with a 5Ah capacity. This is connected to a battery management system (BMS) that provides standard protections such as over-current, over-voltage, under-voltage, and advanced features such as balance charging. The BMS connects to the Worm Main Power Bus (WMPB). The WMPB powers the three motors as well as a step-down converter for the computer and other logic-level electronics. Where the Worm connects to the pallet, a connector is present that allows the WMPB to connect to the WMPBs of all of the other Worms via the Pallet Main Power Bus (PMPB). In this Gen1 proof of concept system, all the WMPBs of all the Worms are simply connected in parallel simulating a 21-motor system connected to one large battery. The pallet battery is also connected to this PMPB which adds additional capacity and therefore runtime. This system allows all the Worms to share power but it doesn't allow for advanced features such as selectable power sharing, Worm disconnection in the event of failure, Worm-to-Worm battery balancing and charging. Species module batteries are not supported in this Gen1 proof of concept, but will be supported in Gen2 and Gen3.

E. WORMS-1 Internal Data Network

The internal data network consists of an inter-Worm network and an intra-Worm network. The intra-Worm network is provided via ethernet cables that run through the Worms and connect to a central router and network switch on the pallet allowing all individual Worm computers to communicate via the ROS2 architecture. The inter-Worm bus is responsible for commands to the actuators and runs from the central computer to each of the actuators. CAN-bus was chosen for its superior reliability in actuation control.

F. WORMS-1 Species Module "Navigator"

A prototype Navigator module is based around the Velodyne VLP-16 LiDAR unit, which is packaged around its own Raspberry Pi processor board, and interface module. The system fits into a standard UIB form factor as shown in Fig. 8, and demonstrates the first version of an interchangeable module with self-contained electronics. The first version of the Navigator stack will incorporate provisions for imaging and gait obstruction detection.

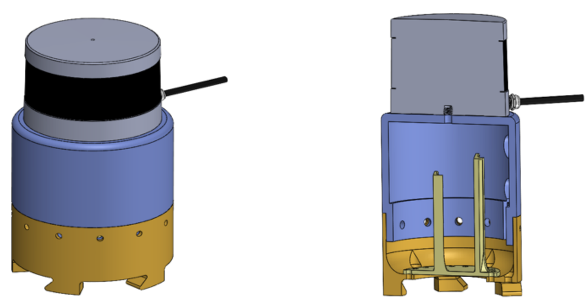

Fig. 8: the "Navigator" species module

V. Potential Applications of the WORMS Architecture

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 depicted in Fig. 9 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 and other robots and instruments 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. Longer term, as the human presence starts to grow, more capable WORMS robot configurations can explore and install power networks and data relay stations inside lava tubes, and support rovers and ISRU systems in and near PSR's. As the size of infrastructure delivered to the lunar South pole grows to multiton units, the third-generation (Gen3) WORMS architecture has been designed to scale up with much more powerful motors and larger Worms to support moving and deploying these infrastructure elements to any point on the lunar surface, whether paved by road or not.

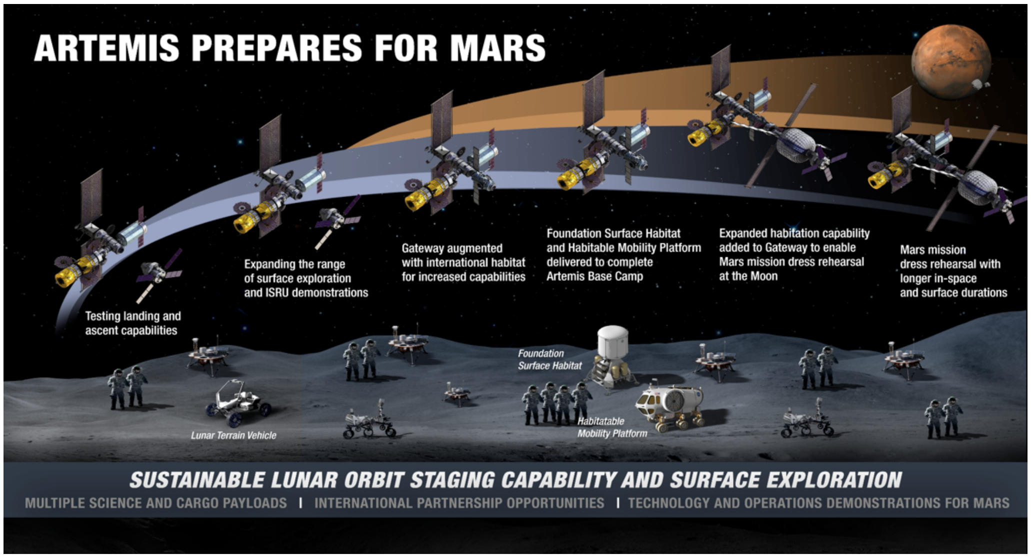

Fig. 9 The Artemis Program will lead to an extended and expanding presence on the Moon and on to Mars. Image credit: NASA

A. Carrying payloads up or down steep inclines (Feasible with Gen1)

NASA is interested in exploring permanently shadowed regions (PSRs) at the lunar South pole, including craters. The entry path into lunar polar craters can be of steep and relatively uneven grade. Traversing such steep paths while delivering heavy payloads would be essential to support the exploration and utilization of the unique environments inside PSRs. A train of mutually supporting hexapods, as shown in Fig 10., can be assembled using Gen1 Worms, pallets, shoes and the Navigator species module. The longer baseline enables the train to slowly descend along a steep path into a crater, delivering heavy payloads carried on the pallets.

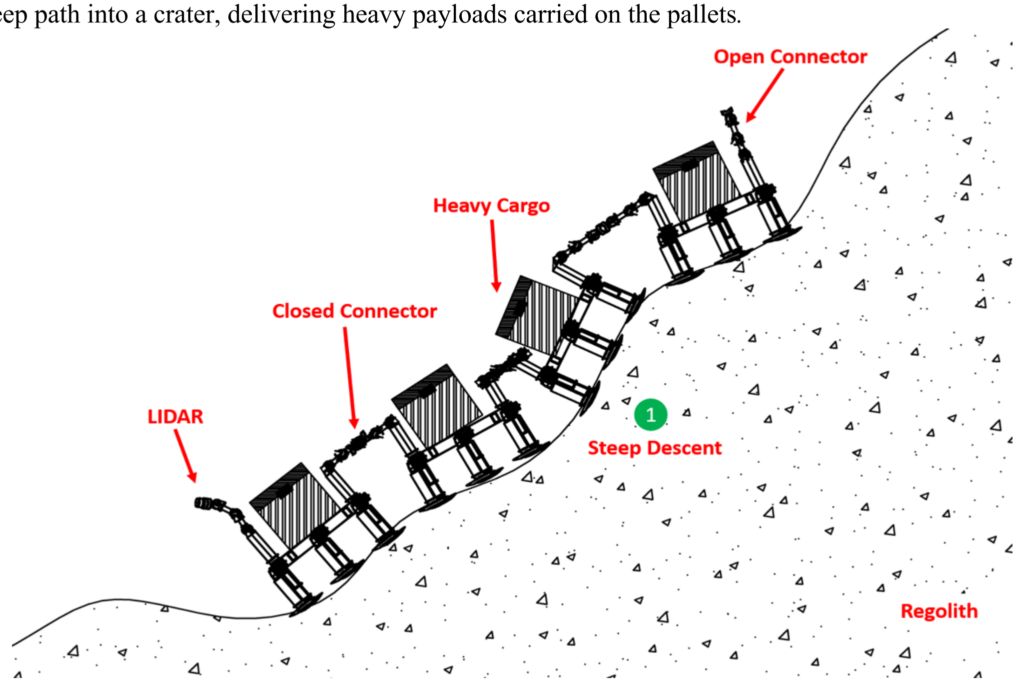

Fig. 10 Traversing Steep Inclines with a train of Gen1 robots

B. Setting Up Recharging Stations inside PSRs for Other Robots or Rovers (Requires Gen2)

Permanently Shadowed Regions (PSR) are believed to harbor water ice and volatiles that are of interest to science and exploration. However, the environment inside PSR's is hostile to exploration due to the extreme cold, darkness and uncertainty regarding the terrain. This makes it challenging to design and operate rovers and robots intended to operate for long periods inside PSRs.

One possible application for a WORMS robot is to traverse to a location inside a PSR and provide a recharging service for other robots or rovers that are exploring that region, as shown in Fig. 11 below. Such a capability would extend the time that these robots and rovers can spend inside the PSR, improving their productivity. This provision of a recharging capability inside a PSR can be accomplished using a specialized hexapod configured out of Gen2 Worms. For this use case, Gen2 would be required for the species module support to unspool a power cable behind the WORMS robot (the "Winch" species module) and also for species module support to expose a charging port interface as one of the end effectors (the "Charger" species module). This WORMS robot would depart from the lander and travel toward a nearby crater, unspooling behind it a power cable that connects to a power source. Using the Rounded Shoe accessory, it will navigate porous or rocky terrain and descend the steep crater slope to reach a location inside the PSR, where it will park itself. With power supplied from the unspooled cable, its free 4DOF arm, which has a "Charger" module at the end compatible with charging ports on other assets, will offer charging services to other robots.

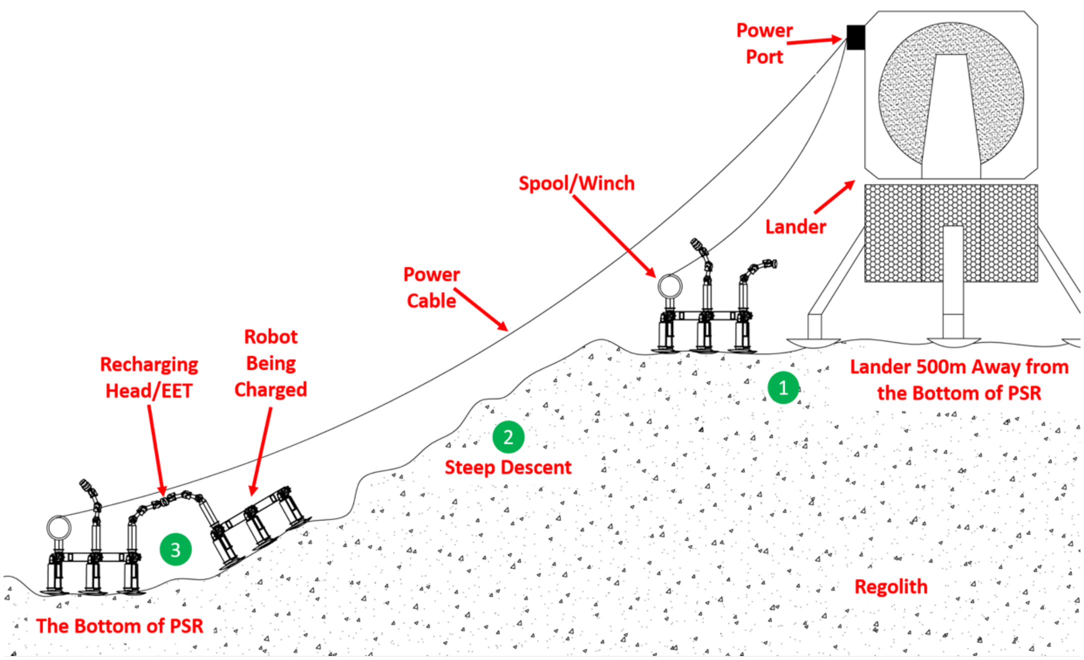

Fig. 11 Setting up a Charging Station inside a PSR for other robots or rovers

C. Carrying an LVSAT to a Peak of Eternal Light for Deployment (Requires Gen2)

The lunar terrain consists of uneven, often steep terrain. Traversing this terrain would be essential to support the development of infrastructure on the moon. Higher altitude surfaces of the moon especially, would be ideal to host solar panels for energy collection as there would be fewer surrounding obstacles to prevent this area from being shadowed. NASA and their partners are working to develop vertically deployable solar array systems for the lunar surface (LVSATs). The hope is to use this power source to establish a sustainable presence at the lunar South pole [34]. 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.

This application would require a Gen2 WORM for its species module functionalities. The scaled-up WORMS Gen2 architecture will be able to hold at least 900kg in a hexapod configuration, making it a great system to carry large, heavy payloads such as LVSATs. An Ox-Goat arrangement of the WORMS can be used here, as shown in Fig. 12 below. The ox and goat arrangements will be tethered via a WORM with a winch and cable species module. First, the skilled climber - the goat - will traverse up the hill while winching out enough cable to leave the ox arrangement at the bottom of the hill. Once the goat has reached its destination, it will use Worms specialized with Anchor species modules to drill into the ground, securing itself for the winching operation. The ox will carry the necessary payload and will be pulled up by the goat via the winch species module. The anchors on the goat will prevent it from slipping back down the hill. A Navigator species module can be used by the goat as it traverses up the hill to plan its path and reach the top of the hill with ease. The WORMS software architecture will be leveraged here to provide the coordination between the two "separate" goat and ox WORMS robot configurations.

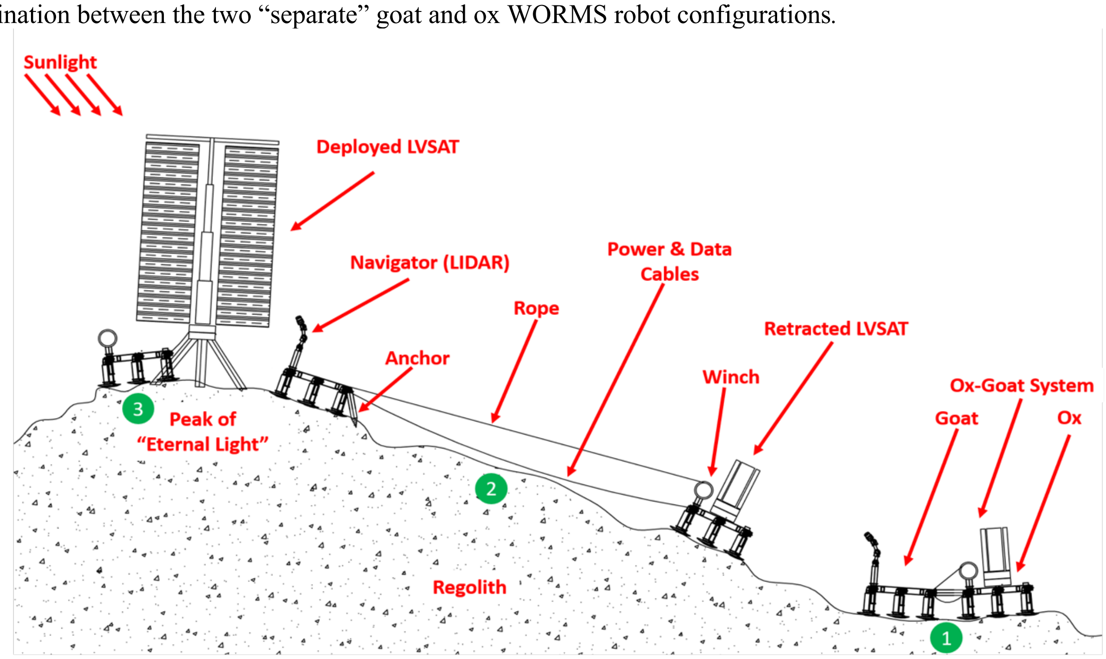

Fig. 12 Carrying a high-mass LVSAT to a "peak of eternal light" for deployment

D. Exploring Lava Tubes using tandems of WORMS Carriers and Walkers (Requires Gen3)

Just like the permanently shadowed region, the lava tubes on the Moon have also been an interesting target for lunar exploration. In terms of the scientific value of lunar lava tube, study on the multiple layers of basalt on the ceiling of a lava tube can shed insight on the compositions of the Moon's mantle that are melted over different eras and thus the geographic history of the Moon [35]. In terms of the value for human habitation, the ceilings of the lava tubes are estimated to be over 10-meter thick which can potentially provide shelter from micro-meteoritic bombardments, space radiations, and extreme temperature variations [36,37]. In addition, there has also been research indicating the potential abundance of Titanium and Helium ores near the lava tubes on Marius Hills and Mare Tranquilitatis, which can be utilized in the construction of human habitat [38]. Therefore, the exploration of the Moon's lava tubes becomes valuable for future missions.

Before human exploration in a lunar lava tube, an autonomous robotic examination of the tunnel can assist in identifying potential hazards for future human settlement. Therefore, one potential application of the WORMS architecture is the exploration lunar lava tubes. As the estimated depths of the pit openings range from 45 to 100 meters, rappelling down a WORMS walker off the edge of the opening will be the method utilized in this application [38]. As illustrated in Fig. 13, a Gen3 WORMS carrier with an expanded payload capacity will first carry a lightweight Gen2 / Gen1 WORMS walker to the edge of the pit opening. The convex pad shoes of the carrier will prevent itself and the walker from sinking into the regolith when walking towards the cliff. 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 the arm 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.

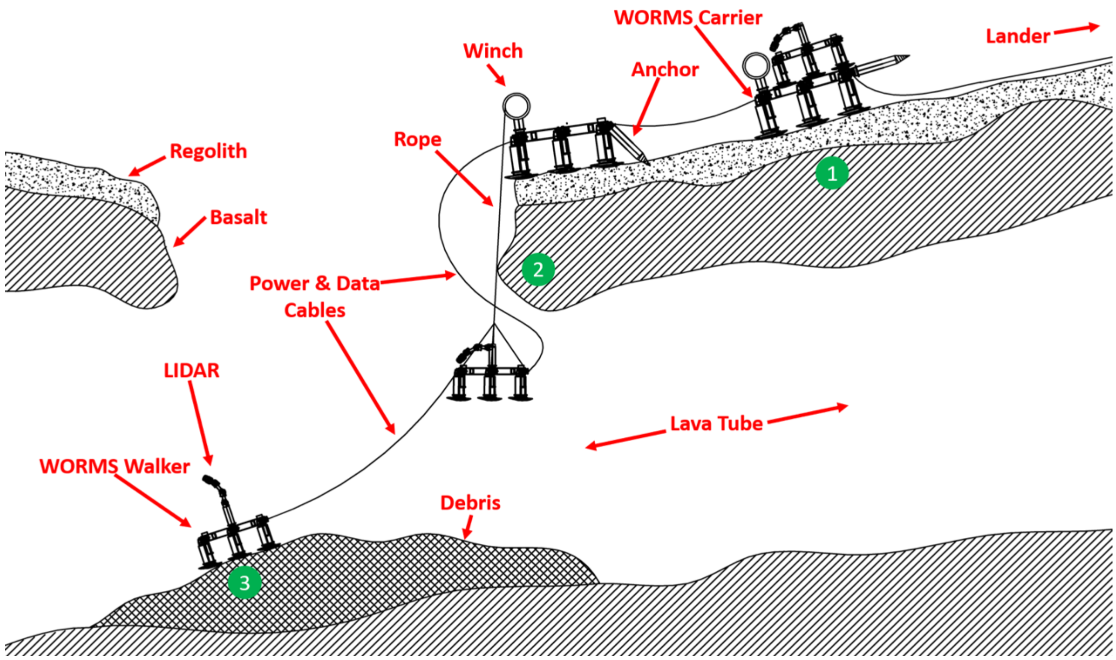

Fig. 13 Exploring Lava Tubes Using Pairs of WORMS carrier and walker

Upon reaching the floor of the lava tube, the walker, equipped with a Navigator species module, lights and any required instruments, may detach from the carrier on the surface and start autonomously exploring the lava tube. Alternatively, the walker in the tube may stay connected to the carrier and act as a power and data relay for the other walkers exploring the tube. Once the exploration is completed, the walker can be lifted back to the surface by the carrier which will later return back to the lander. Compared to a traditional wheel or caterpillar-based robot, a WORMS walker with a capability of climbing up high-gradient slanted surfaces covered by porous regolith may be more suitable for the exploration of lunar lava tubes.

E. Laying and picking up climbing anchors to support traversal of very steep inclines (Requires Gen3)

The topological gradients of the Moon vary considerably, especially near craters. Testing and studying these craters are not essential to learning about the history of the Moon, but also may help NASA identify areas of the Moon that are rich in water or other resources. Craters near the lunar South Pole, for example, are expected to have the highest concentrations of water ice which would be vital for future human settlement and further lunar exploration. Therefore, developing technologies to explore the regions within craters is of significant importance. VIPER is one example of a robot being developed by NASA which has the goal of exploring the South Pole to gauge the location of water ice on the Moon [27].

To further space exploration, there must be more investigation done to ascertain the location and concentration of water ice and other resources within craters on the lunar surface. The main challenge here lies in traversing the steep slopes of such craters. The modularity and reconfigurability of the Gen3 WORMS system enables it to offer a potential solution to this mobility challenge. An illustration of the approach is shown in Fig. 14 below. The Gen3 Worm offers all the advantages of the Gen2 species modules addition, allowing the Worm robot to have a drill-based anchor module to anchor itself into the lunar surface. Once the anchor is in place, the system is winched down into the crater via a cable and the anchor detaches from the system so the WORMS robot can explore. The Gen3 Worm explores the area and performs all the data collection using the Navigator and other sensor species modules. Once the system has completed its data collection it must return to pick up its released anchor. With the new capabilities of the Gen3 Worm, the system is able to autonomously reconfigure itself and attach the end of the anchor back onto its body, to winch itself up.

The Gen3 will be large and will possess the capacity to carry large payloads. This is advantageous because the robot can carry large payloads down steep hills which may be required for various applications such as transporting a resource mining system to a hard-to-reach location of high resource concentration, or even another WORMS robot (or a wheeled rover) across rough terrain.

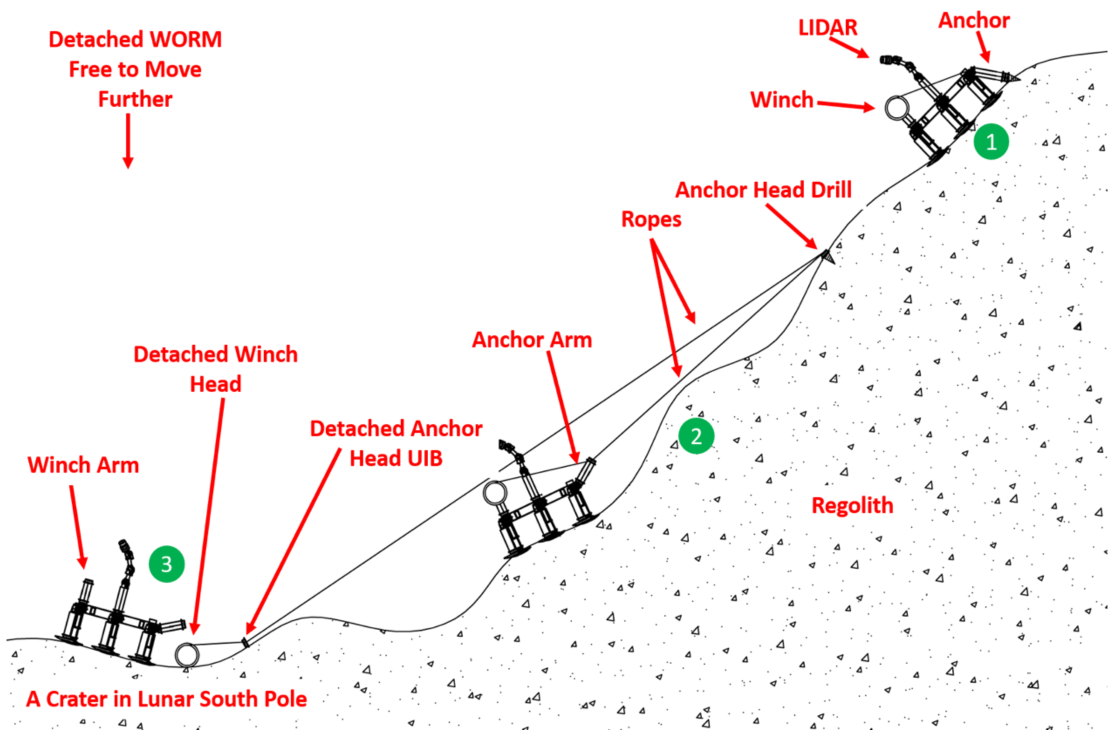

Fig. 14 Laying and picking up climbing anchors to support traversal of very steep inclines

VI. Discussion and Conclusion

WORMS trades unit-level performance and efficiency for versatility and lower system cost. The WORMS architecture is designed with interchangeable components for more versatility; different Worms, species modules and accessories such as pallets and shoes can be customized and attached at the UIB interface. The price of modularity is higher complexity and higher mass relative to a custom design that is tuned for a single application. Rather than perfection in any use case, WORMS derives its value from its ability to adequately meet the demands of a large number of use cases. As articulated above, the modularity of this architecture allows astronauts to easily create robot configurations for exploring terrain ranging from resource-rich lava tubes to ice-packed craters, supporting objectives from payload transportation to resource reconnaissance and infrastructure deployment and development. This paper lists only a sample of five applications of WORMS, however there are many other possible combinations of Worms, accessories, and species modules which allow this architecture to tackle unplanned, changing, and future needs.

In short, WORMS' modularity results in an array of possible applications, and this versatility of use makes it invaluable to any lunar mission. Beyond modularity, WORMS comes with additional value-adding attributes: learning curve benefits, easy maintainability, mass production cost savings, adaptability, and cross-operability.

A. Learning Curve Benefits

The core of the WORMS infrastructure is the individual WORMS robot, and it is respectively the most complex assembly to manufacture. In typical industrial processes, the manufacturing output and efficiency of a particular product increases as the number of units produced increases [39]. Given that the stock of WORMS parts at a lunar outpost would include a few, relatively inexpensive structural accessories (pallets, shoes), and multiple individual Worm robots, there is a cost benefit associated with needing to manufacture the large number of Worms that will be needed to assemble various system configurations to meet more simultaneous mission demands. In fine, WORMS' modularity reduces the price of manufacturing multiple systems as opposed to traditional one-off robots where the learning benefits are reduced.

B. Easy Maintainability

With Gen1 WORMS robots, once they are back at base in a pressurized environment it is easy to replace a malfunctioning Worm with a new Worm and return the robot to good working order. With Gen2 Worms, astronauts will be able to perform this Worm replacement task in the field, and with Gen3 Worms, some of the Worm replacement process can be autonomous. The operational plan for maintenance is to replace malfunctioning Worms with new / working ones, and to send the failed Worms back to Earth for investigation, learning and repair.

C. Mass Production Cost Savings

As Worms, accessories and species modules will be mass produced to fill many diverse needs for robotic mobility on the Moon, the per unit cost is expected to fall as the non-recurring engineering costs are amortized across many units.

D. Adaptability

Because of WORMS' modularity, a wide assortment of robotic systems armed with different tools can be assembled. This fact renders WORMS capable of adapting to unexpected circumstances during a lunar campaign. For example, if an excursion to a lava tube reveals the presence of a high-value resource such as titanium ore or water, and astronauts found that their mission would benefit from the extraction of a sample, an Astronaut could simply swap out one of the WORMS with a drilling-species-module-specific Worm to meet this new objective. In space exploration, the number of unexpected situations that can arise are innumerable, and many such situations throughout the history of spaceflight have required the assembly of contraptions and mechanisms using existing materials: having such an adaptable capacity with multiple configurations of tools and Worms distinguishes this architecture and makes it invaluable to tackling uncertainty in lunar exploration.

E. Cross-operability

As NASA continues to partner with private and public firms in promoting exploration of the moon and the extraction of its resources with new technologies and systems, a shared infrastructure of robotic reconnaissance units and mission-assisting rovers would facilitate collaboration [40]. The WORMS architecture could serve as a standard and programmable unit that would bridge the gap between partners' technologies due to the Universal Interface Block's innovative method of data, power, and mechanical connection. In essence, partners would be capable of appropriating the WORMS infrastructure to their needs by adopting it as a standard design. For example, if a commercial lunar payload services provider were to add side panels with UIB's, the lander could potentially be relocated by temporarily attaching Gen3 WORMS legs to the lander body and walking it to a more useful (and more dangerous) location [11].

F. Conclusion

The outline for future generations (Gen1-3) allows for smooth integration and backwards compatibility cross-generation. The simpler Gen1 proof of concept showcases key components for an early technology demonstration and their applications, including: multi-jointed Worms; accessories such as rounded shoes for navigating on uneven or porous terrain, or pallets that can carry payload and support power-sharing; basic gait simulations and demonstrations; and a Navigator species module demonstration. As more advanced capabilities are developed, such as added DOF on the Worm limbs, fluidics, and additional sensors, WORMS robots will have broader coverage of potential applications.

The WORMS architecture feeds 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. Our approach is such that WORMS can be a mass-producible, reconfigurable, reusable and scalable system with easily interchangeable major hardware, to better support a range of extreme access needs and various lunar infrastructure development scenarios. The architecture is designed to be resilient, versatile, easily maintainable, low-cost, evolvable, flexible and future-proof. Future generations of WORMS will add scale, features and resilience, expanding the range of use cases and applications in line with the expanding Artemis Base Camp and its needs.

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