# WORMS: Field-Reconfigurable Robots for Extreme Lunar Terrain

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# WORMS: Field-Reconfigurable Robots for Extreme Lunar Terrain

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*Abstract*—**The 2022 NASA BIG Idea Challenge invited teams to develop novel extreme lunar terrain mobility technologies in support of the Artemis program, setting only the constraint to not propose a wheeled robot. This paper proposes a platform for field-reconfigurable walking robots that can be tailored to multiple missions and even repaired in the field. Design exploration started with listing potential missions for walking robots, and took inspiration from animals to conceptualize four different locomotion strategies and associated novel robot forms. We then synthesized all ideas into our field-reconfigurable robot platform architecture, the Walking Oligomeric Robotic Mobility System (WORMS). The elements of WORMS include identical articulating Worm robots, simple Accessories, such as shoes and chassis or pallets, as well as more sophisticated Species Modules (such as the 'Mapper'). With a variety of elements in hand, different animal-like robots can be rapidly assembled and dispatched to support many different mission profiles. Specialization of function is accomplished using a variety of modular Accessories and Species Modules, such as different shoes, an anchoring drill, or a winch-and-cable. Each known robot configuration requires only the needed hardware elements plus software, meaning that new robots can be transmitted to the Moon. The system is designed for ease of assembly, operations and maintenance by non-specialists. In our WORMS-1 proof of concept which is presented here, six Worms with large Apollo-like shoes serve as legs to traverse high-porosity and steeply inclined terrain in order to set up a charging and radio relay station for other rovers inside permanently shadowed regions. Different robot configurations, working alone or in swarms, could traverse other terrain types and perform different missions. WORMS is enabled by three key technologies: (1) the Worm robot itself; (2) the universal interface block (UIB) which is a common mating adapter for all mechanical, electrical and data connections between Worms, Accessories and Species Modules and (3) the ability to safely share electrical power between Worms. In the paper, we present the architecture, trade studies, test results and path-to-flight considerations to evolve the as-built proof of concept WORMS-1 from its current Technology Readiness Level (TRL) 4 into a future TRL 6 design. We also describe the methods and lessons learned from our step-by-step architecting process, which included brainstorming, concept generation and concept fusion into a versatile platform design. We propose that WORMS is a resilient, easily maintainable, low-cost, evolvable, flexible, future-proof and modular architecture for the rapid field assembly of robots to support extreme terrain access and lunar infrastructure development. WORMS can therefore support many of the needs of NASA and its commercial and industrial partners throughout the Artemis program and on to Mars and beyond.**

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## 1. INTRODUCTION

The National Aeronautics and Space Administration (NASA) is planning a return to the Moon with the Artemis program in the second half of this decade. Following the Artemis III landing near the lunar South pole, currently planned for 2025, NASA intends to establish a permanent presence there starting with the Artemis Base Camp. In the next decade, it is expected that NASA's international and commercial partners will contribute to the expansion of this base camp. Over the long term, it is likely that there will be substantial, increasing, evolving, and diverse needs for extreme terrain mobility in the vicinity of the Artemis Base Camp at the lunar South pole to support science, exploration, and infrastructure development.

These needs will include laying cables and pipelines, mining, transporting, processing and storing in situ resources, building roads over extreme terrain, erecting towers and antenna masts, deploying solar power arrays and nuclear reactors and connecting them to a power grid, building habitats and radiation shields, moving large science and exploration equipment or even entire habitats to their deployment location, and exploring and mapping lava tubes, permanently shadowed regions (PSRs), pits, ridges, steep slopes and crevices.

However, rovers with flight heritage are based on wheeled architectures intended for safe landing locations that were selected for past human and robotic missions. New mobility solutions that are not dependent on wheeled mobility are required, and some are currently in development; however, each targets a subset of extreme terrain, and there isn't one

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**Figure 1**: **Artemis Program artists' impression (NASA).**

robotic architecture that could be readily adapted to support a mobility capability for every kind of extreme terrain.

Thus, as NASA and its international and commercial partners start to expand the Artemis Base Camp in the next decade (Figure 1), there is a risk that a zoo of incompatible robots will start accumulating on the Moon, leading to inefficiencies, potentially unmet needs and complicating the supportability of the robots supporting human operations on the Moon. This leads to our research question: how to architect a new robotics platform of field-reconfigurable lunar robots that could meet current or future extreme terrain mobility needs?

## 2. Literature Review

As a first step for our design and technology demonstration, we decided to initially limit our scope to lunar robotic mobility in high-porosity regolith and/or steep slopes, but also to preserve the option of accessing other types of extreme terrain with the same or similar technologies, if at all possible. To better understand our design space, we first researched the terrain at the lunar poles as well as current and planned mobility solutions. At the highlands in the lunar South Pole, high-porosity regolith thickness can reach up to 10-15m in depth. This is significantly thicker than the 3-5m depth of the mare regions [1]. Traversing this, especially on steep slopes, is hazardous due to the loosely packed nature of the regolith. Regolith also surrounds the Permanently Shadowed Regions (PSRs) of the moon. There is considerable evidence that PSRs contain water-ice and other preserved volatiles [2], [3], [4]; consequently, exploring these areas is of significant importance. Between the lunar mares and highland regions there are many lunar lava tubes - likely ranging from 1600 to 3000 feet [5], [6], [7]. These large structures are being investigated for their habitability, however the deep pits require novel mobility solutions for further exploration.

We looked into crewed and robotic lunar mobility solutions either available or currently under development, such as ATHLETE [8], LTV [9], VIPER [10], PUFFER [11] and RASSOR [12]. All mobility solutions use wheels, though ATHLETE and RASSOR can also articulate to cross terrain that would otherwise have been impassable. VIPER plans to use wheel technology that can also "walk" by moving its wheels independently as well as headlights to explore dark craters [10]. Wheeled rovers are at risk of getting bogged down in high-porosity, loosely compacted regolith traps - a fate that befell NASA's Spirit rover on Mars [13], while RASSOR, a robot designed for traversing and excavating regolith, could handle loosely compacted terrain on level ground, but was unable to climb a 30-degree slope due to the shearing and avalanching of the regolith under its weight [12]. We also looked into the Apollo lander footpads used to rest atop regolith as inspiration for the first prototype footpads of a walking robot.

From our review, we noted that most current or planned mobility solutions were too closely optimized for a limited range of extreme terrain and we decided to challenge that design approach. We set ourselves the goal to search for a single set of technologies to address diverse mobility challenges that restrict access to high-value extreme terrain, such as high porosity regolith, steep slopes, high sunlit peaks, PSRs and lava tubes. Ultimately, our review of the state of the art helped place terrain traversal challenges in perspective and informed our search of the design space for a new mobility modality – a new robotics platform - that could be adapted not just to different types of extreme terrain topography, but also to a variety of mission concepts and stakeholder needs.

## 3. Concept Generation and Selection

*Stakeholder Needs*

The next step was to identify the Artemis Program stakeholders and all the value exchanges that take place between them and the WORMS project, as shown in Figure 2.

*Mapping Value to Needs*

In our exploration of the design space, which ultimately led to architecting a field-reconfigurable robotics platform for lunar surface operations, we started by mapping the identified 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 (Table 1, Q1). For example, most stakeholders shown in Figure 2, such as NASA and its international and space industry partners, will need to power and maintain their fixed and mobile systems, explore the region, and so on. Thus, "positioning solar arrays and power banks at crater rims and hilltops" may be valued by several stakeholders because it enables the design of smaller rovers that can rely on a solar-powered charging network. Up to here, our concepts were still solution-neutral.

*From Overfitted Architectures to Reconfigurable Platforms*

The next step was to brainstorm different robot concepts and see which robots can carry out which missions (Table 1, Q2). So, for example, if a concept includes words such as "using a biomimetic goat robot", then it becomes solution-specific. Next, we downselected to a few externally delivered functions (Table 1, Q3) and to a few related robot concepts. We investigated internal functions and outlined alternative "good" internal functional architectures (Table 1, Q4) that could deliver the external functions.

Looking closely at the 2-3 missions and the 2-3 robot concepts, we continued with a comparative discussion of the alternative missions and robot concepts, starting with what metric(s) should be used. We sought ways to combine missions and external functions in an effort to capture more value without adding more parts. We asked ourselves, what are some ways to achieve that? Could a part deliver more than one internal function? For example, legs can perform LIFTING, CARRYING, WALKING, JUMPING and even THROWING.

A key step leading us closer to a platform architecture was to start synthesizing some alternative integrated concepts which

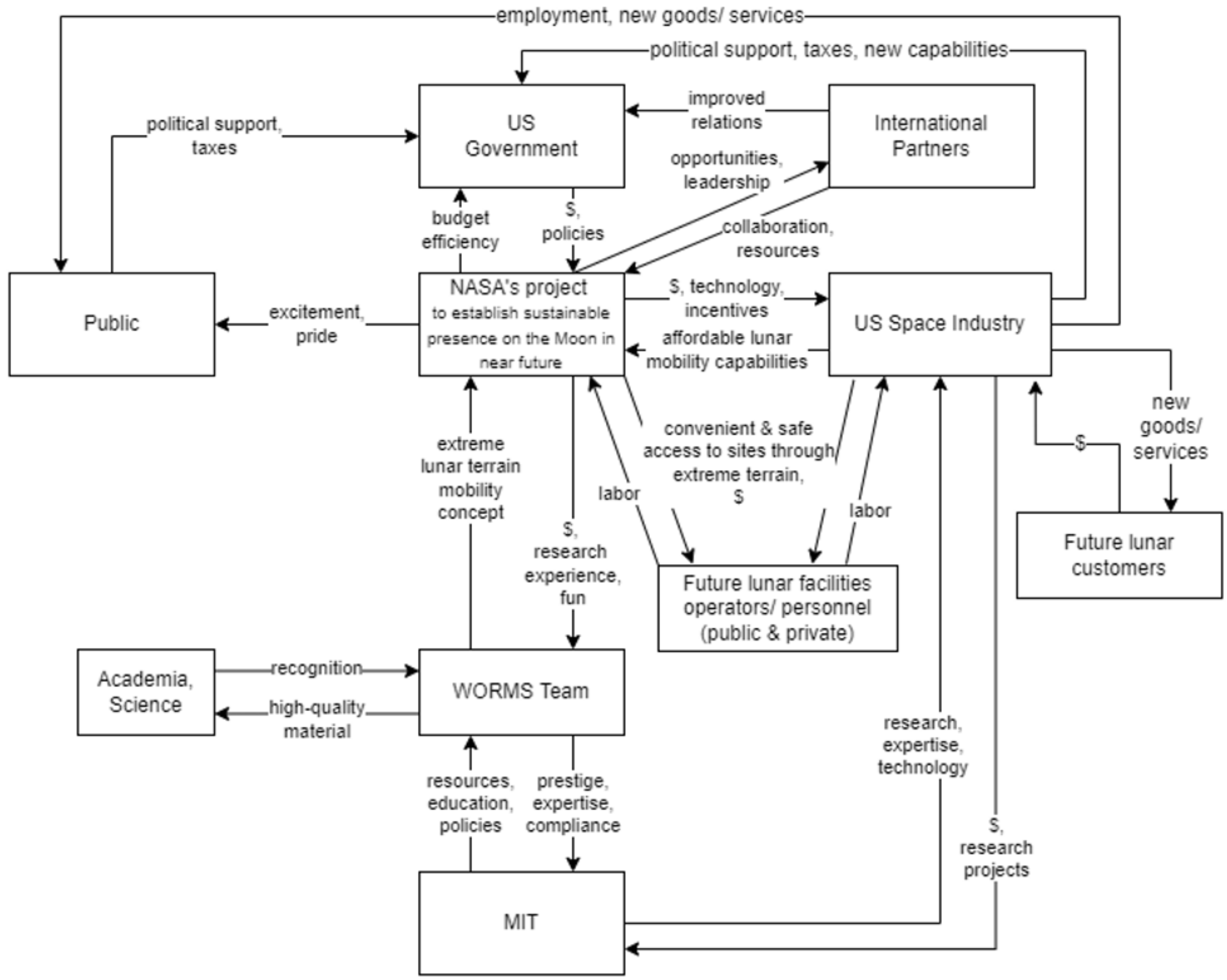



**Figure 2**: **Stakeholder Value Network graph for Lunar Extreme Terrain Mobility.**

offer high 'value' at low 'cost'. This was accomplished by taking the decomposed internal functions and forms of each canonical robot form, adapting them to reduce the number of forms and providing them with standardized interfaces between Worms and other elements, while still retaining the capability to deliver all the internal functions. This set us on a path to answering the last question, Q5 of Table 1. We did that by assigning multiple functions to a single element of form, which ultimately became the Worm, and this eventually gave rise to our platform concept. The critical step was to review the subsystem-level elements of form that would be required to implement several different missions and ask the following questions: Could the subsystems be adapted and standardized so as to minimize the number of unique elements? Could they be fitted with a universal interfacing system, so as to give rise to a family of reconfigurable robots made up of several Worms? Could each animal-like robot have different capabilities, and deliver a different type of external value?

*Using Lifecycle Properties to Inform Concept Selection*

However, before answering the above questions and arriving at the design for our platform, we took two more steps to inform our remaining design decisions. The first was to consider the set of desirable lifecycle properties that these subsystem-level elements should exhibit, and the second was to map these to potential use cases. In this way, we sought to optimize form to not just enable the chosen external and internal functions, but to do so in the context of actual use cases and a long useful life on the Moon. These lifecycle properties are commonly referred to as -ilities.

Our starting point for this analysis was reviewing attribute words that (typically) end in -ility and which are generally shared by successful robots fielded by NASA and JPL. From these exercises, we noted the attributes of "reliability", "simplicity", "modularity", "operational flexibility". We then went back to our stakeholder analysis which included commercial and international partners, and added the lifecycle properties of "scalability", "interoperability", "reusability" and "reconfigurability" to align with what we felt would be strategic priorities that they might care about, given NASA's strategic vision [14]. We note that some of these properties interact with others, for example a reliable system is more likely to be reusable and therefore reconfigurable, and a modular or reconfigurable system would be more likely to also exhibit high levels of operational flexibility.

**Table 1**: **System Architecting Steps leading to a Reconfigurable Robotics Platform for Lunar Surface Operations**

| **System Architecting Questions** | **Decision Type** | **Level** | **Examples** |
|---|---|---|---|
| Q1: What is the externally delivered value? | External Function (Process + Operand) | Stakeholder Value delivered by System | e.g. ”Laying power cable through extreme terrain”, ”Mapping a lava tube” etc. |
| Q2: For each externally delivered value and associated system-level functionality, what is a form of robot that could deliver it? | Form + Function (i.e. Architecture) | System | e.g. bio-inspired robots based on an Ox, Goat, Spider, Crab, Turtle, a train of Elephants, Human Mountain Climbers, etc. |
| Q3: For each canonical robot form, what are the internal functions required? | Internal Function | Subsystem Functions | e.g. moving, navigating, traversing X type of terrain, carrying payload, powering, communicating, etc. |
| Q4: For each internal function within each canonical robot, what are the instruments of form required? | Internal Form | Subsystem Forms | e.g. leg, arm, LIDAR, footpad, chassis, power distribution, command and control, radio, etc. |
| Q5: For all internal functions, can their instruments of form be adapted so as to be field-configurable into a variety of canonical robot forms, each delivering a different type of external value? | Standardizing Internal Form to support multiple architectures and external value functions | Systems of Systems | e.g. a standardized “worm” could perform the function of a leg, arm, neck or backbone, and could interface with standardized peripherals that can help specialize its function to meet a need. |

Thus, the next step leading to concept selection was to map this list of “desirable attributes” to a diverse list of near-term lunar surface operations use cases and to the canonical robot architecture forms that could enable them. In doing so, we were seeking to establish whether, if a robot has many of the “desirable attributes”, and if it can support many of the diverse use cases, then that robot form could be perceived as delivering more “value” over time.

*Rapid Prototyping*

A rapid prototyping session allowed us to combine the brainstormed mobility modes and applications into concrete ideas. The team split into pairs and each pair tapped into the previous brainstorming results to come up with a new mobility concept for a mission of their choice. With the guidance of our lists, we were able to draw from nature, existing designs, and topography to make our robots. We had thirty minutes to design what we found most exciting, innovative, and useful to future NASA missions. The pairs each sketched out their design and application and presented it to the group. This proved to be an insightful exercise for we all had vastly different mobility and mission methods, but could see overlap in ideas or architectures.

*Four Canonical (and different) Robot Forms*

The four mission concepts initially conceived were inspired by spiders, mountain climbers, oxen, and elephants.

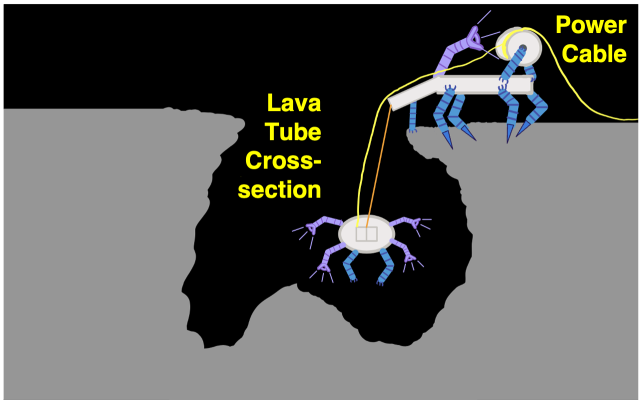
For the spider concept shown in Figure 3a, one pair felt that a dangling robot would be optimal to drop down into lava tubes. This design involved a spider-like robot attached by a tether to an anchored winch. The anchor would sit at the edge of the skylight rim and unspool the spider robot to drop down and traverse the unknown terrain.

Taking note of the regolith’s loose compaction property in places, one team designed a Mountain Climber robot shown in Figure 3b, capable of pulling itself up or rappelling down uncompacted regolith while carrying a payload.

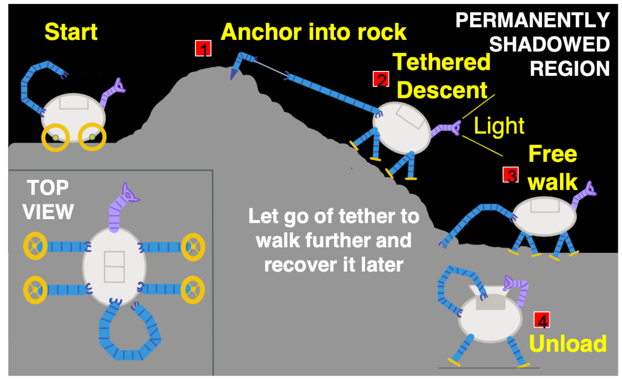
Another pairs’ ’goat & ox’ concept drew inspiration from pairing the strength of an ox with the nimbleness of a goat; In this system shown in Figure 3c, the ’goat’ traverses steep terrain and anchors at the top while the tethered ’ox’ follows behind carrying a heavy payload. In this concept, the goat provides the vital tether which prevents the ox from slipping during its steep climb.

Lastly, drawing inspiration from elephants walking nose-to-tail and their sheer strength inspired a linked system of robots shown in Figure 3d each carrying a heavy payload while connected end to end. The nose-to-tail connections between the robots give rise to a long multi-legged train which helps prevent slippage and tipping during a steep descent or ascent.

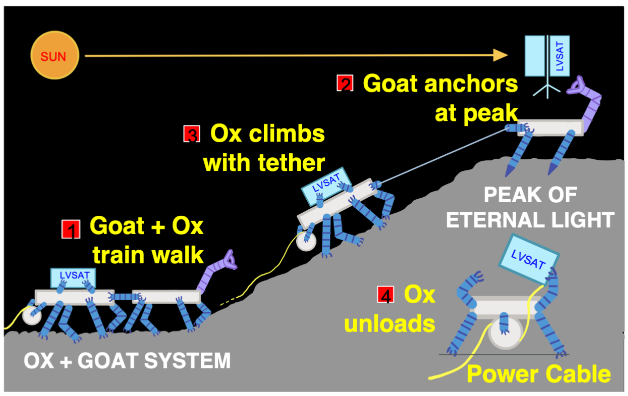
We then went through the four concepts and benchmarked each of them against the list of attributes and the use cases, but also against its own claimed attributes and use cases. Ultimately, this approach guided our architectural decision-making. Tables 5 and 6, in the Appendix, map the four canonical robot forms to use cases and lifecycle properties.



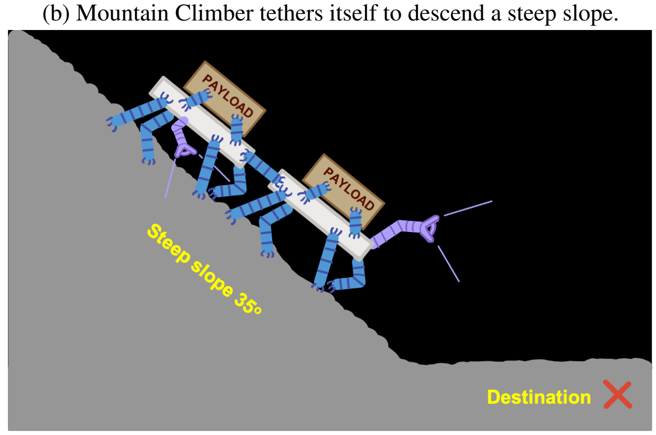

(a) "Spider" lava tube walker deployed by anchored mobile winch platform.




(b) Mountain Climber tethers itself to descend a steep slope.




(c) A Goat and an Ox collaborating to deliver a heavy Lunar Vertical Solar Array (LVSAT) payload onto a 'Peak of Eternal Light'.




(d) Trains of two or more 'elephants' join together for better grip and stability to descend a steep slope.

**Figure 3**: **Four mission concepts developed with rapid prototyping.**

*Synthesis of Four Concepts into One Platform*

The final step in the transformation from disparate architectures, each of which was optimized for a different mission, into a platform capable of supporting multiple use cases while embodying the desired lifecycle properties, was to replace disparate legs, arms, necks and backbones with a single element, the 'Worm', and to provide for a universal interface at the connection between Worms and other parts of a robot body, such as a chassis or 'shoes'.

The result of the first round of ideation in Fall 2021 was our initial Walking Oligomeric Robotic Mobility System (WORMS) architecture shown in Figure 4, which went through several iterations of design and trade studies before maturing into a feasible architecture. The current proof of concept, in its final design iteration as of August 2022, is shown in Figure 5.

## 4. The WORMS Platform Architecture

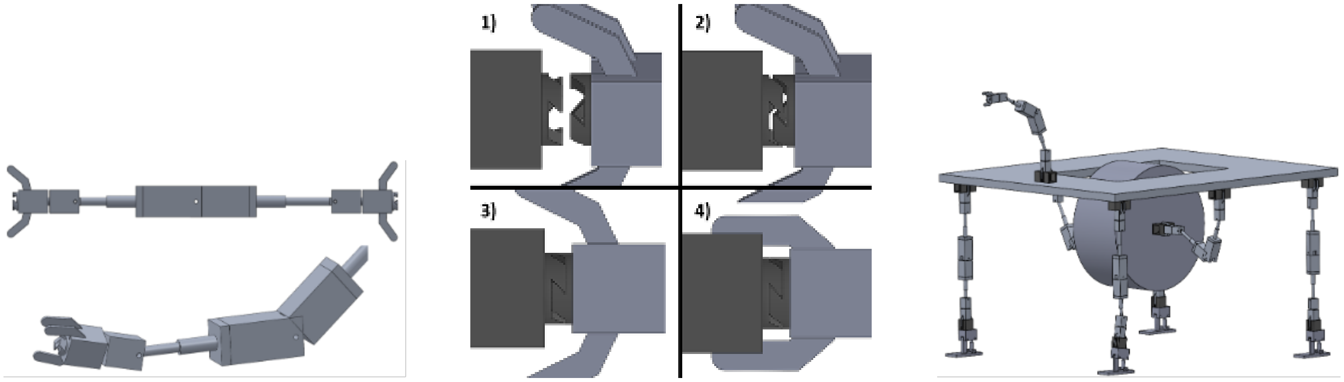
*Types of Architecture Elements*

There are three main categories of the WORMS modular elements: Worms, Species Modules, and Accessories. The Worms support mobility and load-bearing capacity, the Species modules can be used to add specialized capabilities to a worm, and Accessories are simple mechanical or structural forms that meet specific functional needs. Examples include Shoes for walking, or a Pallet to carry payloads and provide a body chassis.

*Three Generations of Worms*

Within each generation, individual Worms are designed to be identical and interchangeable. In the current proof-of-concept generation, Generation 1 (Gen 1), Worms can share electrical power, communicate with each other for coordination purposes, have three joints in two perpendicular planes and can carry 400kg of payload on the Moon in a hexapod configuration. In future, the Generation 2 (Gen 2) Worms will have one more degree of freedom and additional built-in capabilities, a larger variety of accessories and species modules for specialized capabilities, and double the endurance / payload capacity of Gen 1. Long term, Generation 3 (Gen 3) will have a fifth degree of freedom, more built-in capabilities including the ability to autonomously connect and disconnect with other architecture elements, as well as significantly heavier and somewhat longer worms for a much larger payload class of the order of nearly 2 tons for a hexapod robot [15].

*Gen 1 (current)*—The proof-of-concept WORMS-1 hexapod was assembled using the first Gen 1 Worms for the purpose of demonstrating key technologies and capabilities. These




(a) Preliminary Worm design (b) Preliminary UIB design (c) Preliminary WORMS robot design

**Figure 4**: **The original conceptual WORMS platform architecture as at the end of ideation, Nov 2021.**

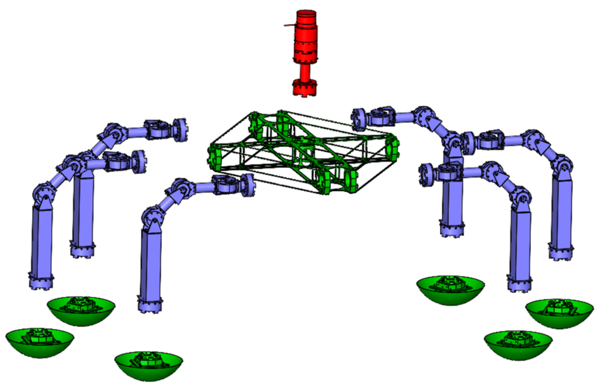


**Figure 5**: **WORMS Gen 1 architecture, as at August 2022.**

include androgynous Universal Interface Blocks (UIB) with a manual connection / disconnection protocol, a minimal three-degree-of-freedom (3 DOF) articulation capability, a basic power-sharing architecture using natural dynamics and a ROS 2 node messaging architecture for command, control and coordination between the independent Worms. A "Mapper" Species module using LiDAR is also demonstrated as a pathfinder, to inform the design of a universal power, data and mechanical interface for potential future Species modules. The Gen 1 platform serves as a technology demonstration to prove the functionality and usefulness of the key enabling WORMS technologies, and to inform the development of a more capable Gen 2 platform that can perform a larger variety of useful missions, for a broader range of stakeholders.

*Gen 2 (future)*— Generation 2 (Gen 2) Worms will have more advanced capabilities, including an additional degree of freedom, a larger mass and payload capability, more on-board sensing capabilities, active power distribution controls and a broader range of accessories and species modules. Gen 2 will exploit the walking gait mechanism to save mass and power through new joint actuator selections. There will also be broader support for sensors such as load cells and IMU's, and for Species Modules carrying drills and other tools, science instruments or additional batteries to allow for more sophisticated and relevant capabilities. The aim of this generation is to provide more functionality and flexibility to crews and Mission control, while standardizing the Species module interface with power and communications.

*Gen 3 (longer term)*— The third generation (Gen 3) of WORMS will focus on even heavier payloads, a more resilient architecture, further additions of new Accessories and Species modules, and a new capability for autonomous reconfiguration. The mass, battery size, and payload capacity would be between 4-6 times larger relative to Gen 1: a Gen 3 hexapod would be able to carry almost 2 tons of payload on the Moon. Gen 3 will contain more advanced integrated electrical and data connections, eliminating the need for external cables or exposed connectors. Another degree of freedom will be included to allow for tipping or tilting of the hip joint, and cameras and sensors will be added to enable autonomous reconfiguration of a WORMS robot.

*Power Distribution Subsystem Overview*

Each Gen 1 Worms' power distribution system consists of a 6-cell lithium battery with 5Ah capacity connected to a battery management system (BMS) connected to the Worm Main Power Bus (WMPB), which powers the motors and a step-down converter for logic-level electronics. Connectors in the Universal Interface between the Pallet and Worms allow the WMPBs of all worms to be connected to the Pallet Main Power Bus (PMPB) for power sharing.

*Universal Interface Block Overview*

All Worms, all Species modules and all Accessories terminate at a Universal Interface Block (UIB), Figure 6, which was designed to provide an easy, rigid and secure attachment mechanism for attaching and removing WORMS architecture elements. The androgynous, axially symmetric UIB interface has 5 jaws on each side with spring loaded pins that lock once the Worm is attached. A helper wedge tool is utilized during disassembly. In Gen 2, the mechanisms will be redesigned for easier in-field disassembly without external tools and will also include power and data sharing capabilities. In Gen 3, the mechanism will be redesigned again for autonomous connection and disconnection, allowing robots to reconfigure themselves during a mission.

*Species Modules Overview*

To demonstrate a Species module for the WORMS platform, a 'Mapper' module was designed and built, Figure 7. This module terminates in the standard Universal Interface Block

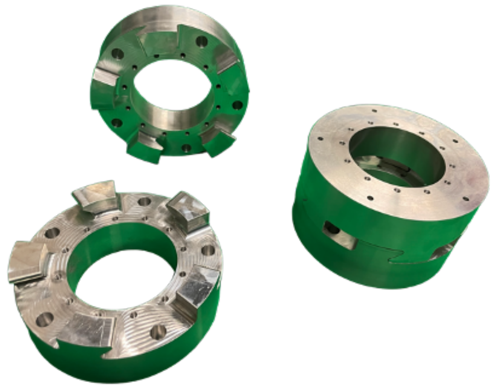


**Figure 6**: **An androgynous universal interface connects all architecture elements. It can be unlocked using a tool.**

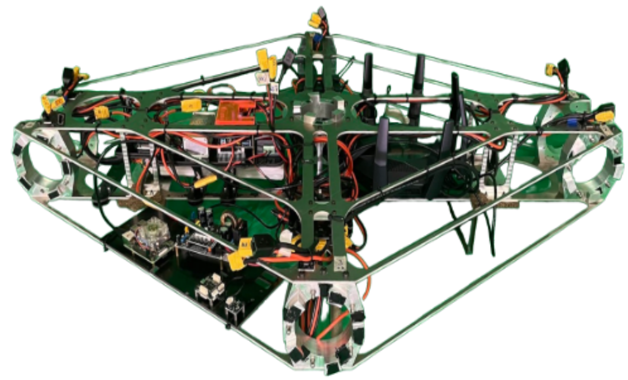


**Figure 8**: **The prototype Pallet accessory has 7 UIB connections and also hosts the pallet main power bus, a pallet battery and a WiFi router (Dimensions: 1300 x 1000mm).**

**Figure 7**: **Our pathfinder species module, 'Mapper', has a LIDAR and command-and-control capabilities.**

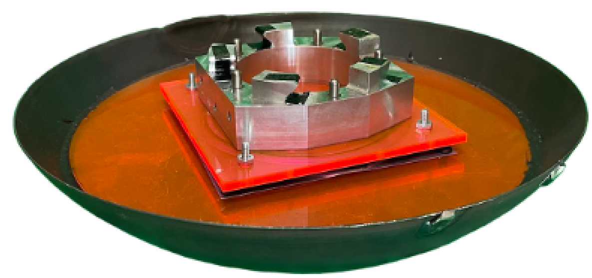


**Figure 9**: **The prototype shoe accessory is rounded for all-round performance on rocky and loosely compacted terrain.**

design, supporting its attachment to either a Worm or to an Accessory such as the Pallet (chassis). The internal electronics are mounted inside the Species module 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 embedded computer and the Velodyne interface board. The Gen 1 Mapper module draws power from its host's power bus (Worm or Pallet Main Power Bus), using ad-hoc adapters and connections; in future generations, Species modules will have standardized voltages and standardized power and data connections. The Gen 1 Mapper module is designed to perform command, control and coordination of all the leg Worms to execute the coordinated walking gait. It can also carry out obstacle detection, with possible extension to sensing large terrain features so that the gait may be adapted for hilly terrain and navigating around obstacles.

*Accessories Overview*

*Pallet (chassis)*—The primary functions of the Pallet, shown in Figure 8, are to provide a lightweight but structurally rigid base for attaching six leg Worms and the Mapper Species module, to provide a Pallet Main Power Bus (PMPB) which enables power sharing among the Worms connected to the Pallet, to provide additional energy storage capacity with its own on-board battery unit and to carry payloads. It consists of a double layered aluminum 6061 plate structure bonded by I-beam supports. The two rhombus-shaped plates are heavily pocketed in order to achieve a mass of only 7.67 kg. To reduce mass while maintaining structural strength, the Pallet design integrates the UIB housings as its main supports.

*Shoes*—Multiple shoe designs, including flat, rounded, foldable, and rounded-flat hybrid designs were prototyped and investigated for support and stability over uneven regolith terrain. All shoes went through multiple iterations of design and simulation before prototyping and testing on artificial snow, which mimics regolith properties. The flat shoe sunk the least when weighed down with 14kg on artificial snow. However, the rounded shoe shape allows better contact and stability on rocky surfaces, and enables tip/tilt degrees of freedom when walking over uneven ground. As a compromise between the twin needs to walk on both highly porous and highly uneven non-porous terrain, an Apollo lunar lander-like rounded wok shown in Figure 9 was selected for Gen 1 prototyping.

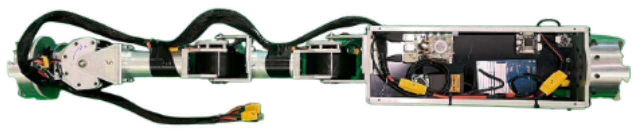


**Figure 10**: **A completed Worm robot**

**Figure 11**: **Worm robot integrated with the pallet (top) and shoe (bottom) using the UIB interfaces.**

*Integration of accessories with Worm Robots*

Figure 10 shows a completed Worm robot. Figure 11 shows a Worm robot securely integrated with the Pallet and Shoe with the UIB interfaces.

## 5. CONCEPT OF OPERATIONS

In the proposed demonstration mission, a WORMS robot powered directly via a tethered cable connected to the lunar lander will walk to the bottom of a Permanently Shadowed Region (PSR), deploy itself as a recharging station, and use its on-board storage to efficiently supply power to other robots and rovers exploring the environment, recharging from the lander whenever convenient. This concept can extend the endurance of robots and rovers for exploration and facilitate the process of terrain mapping within a PSR.

*Mission Requirements*

A mix of Gen 2 and Gen 1 Worm robots, Accessories, and Species Modules are required for this mission mainly due to the need for a variety of operational capabilities and higher torque margins to handle steep inclines while carrying a heavy cable and spool. When the robot descends into the PSR, it will need a "Winch" Species Module to deploy the power cable connected to the lander. If the descent is extremely steep, there are various robot configuration options to complete it safely, such as the goat & ox, mountain climber, or 'train of elephants' concepts explored during preliminary design. Since the recharging robot might be the first robot walking into the unexplored PSR, a Mapper LiDAR module is also needed to avoid obstacles in the descent process. Additionally, a "Charger" Species module on one of the Worms will be used as the recharging port delivering power to other robots and rovers. This "Charger" Species module will have to be specifically designed and manually piloted by Mission Control to close the connection with the charging port on the client. Furthermore, the battery management system (BMS) for this proof-of-concept robot needs to distribute the power from the lunar module into its own battery and those of other robots and rovers.

*Sequence of Operations*

Figure 12 illustrates a sequence of operations. A lunar lander will first land some distance from the rim of the PSR. A WORMS hexapod robot directly powered by the lunar lander via tethered power cable connections will perform a steep descent down to the bottom of the PSR. Once the robot reaches its destination, it will unfold one of its arms terminating in a recharging port Species Module and turn itself into a recharging station continuously powered by the lunar lander. Subsequently, other robots and rovers exploring the same PSR can be recharged by the charging station and can spend more time within the PSR without the need to return to the lander. At the end of its mission, the WORMS-1 hexapod can remain as part of a larger lunar infrastructure, move to a new location, or return to base, with or without the power cable.

## 6. TRADE STUDIES FOR DESIGN DEVELOPMENT

*Initial Sizing Studies*

The WORMS-1 proof of concept robot was initially sized to select a commercial off-the-shelf (COTS) actuator. We used the Hexapod Actuation Calculator [16] to vary the hexapod's mass, limb lengths, walking speed, and ground inclines. From this preliminary investigation, we found that the T-MOTOR AK80-64 actuator's [17] continuous torque rating (48 Nm) and rated speed (57 rpm) can propel a $\sim$100 kg hexapod with $\sim$0.8 m long legs at $\sim$0.1 m/s. Additionally, this configuration can provide more than 30% continuous torque margin throughout the walking gait [15].

*Multi-variable optimization tool and the development of a novel "Magic Carpet" walking gait*

We developed an Excel-based hexapod gait tool to optimize the Worm's size and gait motion. The tool models a single hexapod leg with a set of point masses–representing the foot, actuators, and limbs–and a support force acting on the foot, as shown in Figure 13. Note that the shin remains normal to the local ground, so the gravity forces and the support force are aligned with the shin's central axis on horizontal ground ($\theta$ = 0 degrees). However, on an incline ($\theta > 0$ degrees), these forces are offset from the shin's central axis and cause bending moments and torsional loads throughout the Worm structure.

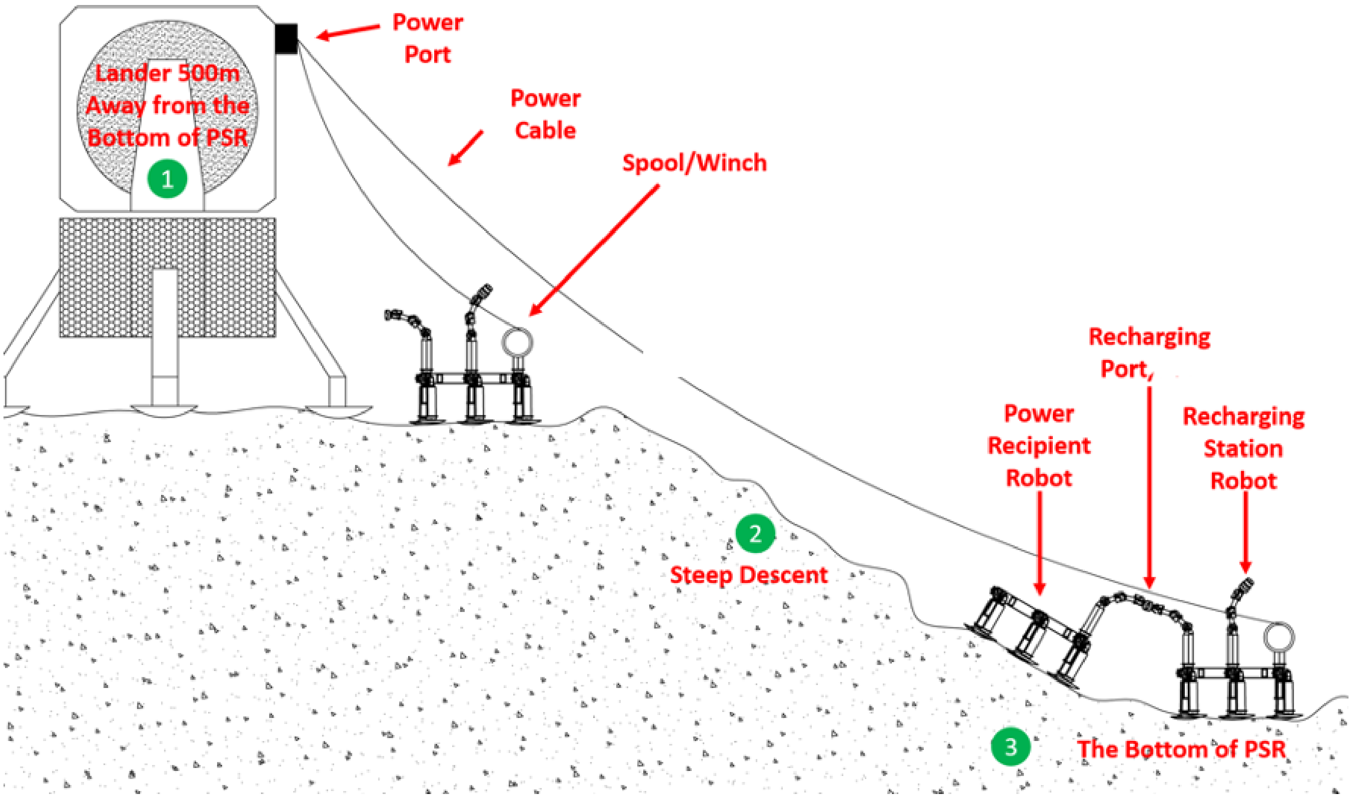



**Figure 12**: **Sequence of Operations of the Proposed 2026 Tech Demonstration Mission: Setting up a Rover / Robot Recharging Station inside a PSR.**

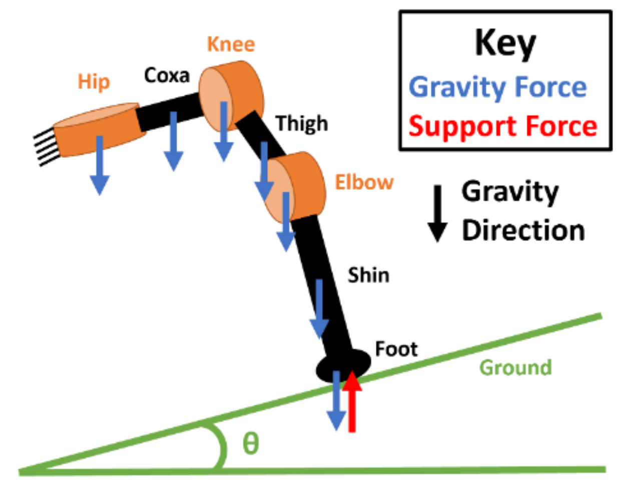



**Figure 13**: **Free body diagram used to model torques at each actuator and define structural load cases on each limb.**

The results of the model apply to any of the six leg worms executing the turtle-like Magic Carpet gait shown in Figure 14. Thus, we expect the Worm's worst-case loading to result from incline walking. The support force acting on the Worm's foot represents the WORMS-1 robot's weight distributed equally between four feet. Additionally, the limbs' center of masses are assumed to be located halfway between their neighboring actuators.

$$\vec{F}_{int}(x) = \sum_i \vec{F}_i \tag{1}$$

$$\vec{\tau}_{int}(x) = \sum_i \vec{r}_{x \to x_i} \times \vec{F}_i \tag{2}$$

The internal forces and moments acting within the Worm are approximated using a statics model, described by Equations 1 and 2.

In (1), only the forces and torques closer to the foot than the point of interest are summed. For example, when calculating the internal forces and moments at the elbow, only the support force and the gravity forces of the shin and foot are considered. In (2), the internal moments at all actuators are tracked throughout the gait to estimate the required torque output of each actuator.

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 in Figure 15.

Note that because the shin uses a statics model and assumes the shin remains normal to the local ground, the tool predicts no torque at the hip and elbow while walking on level ground.

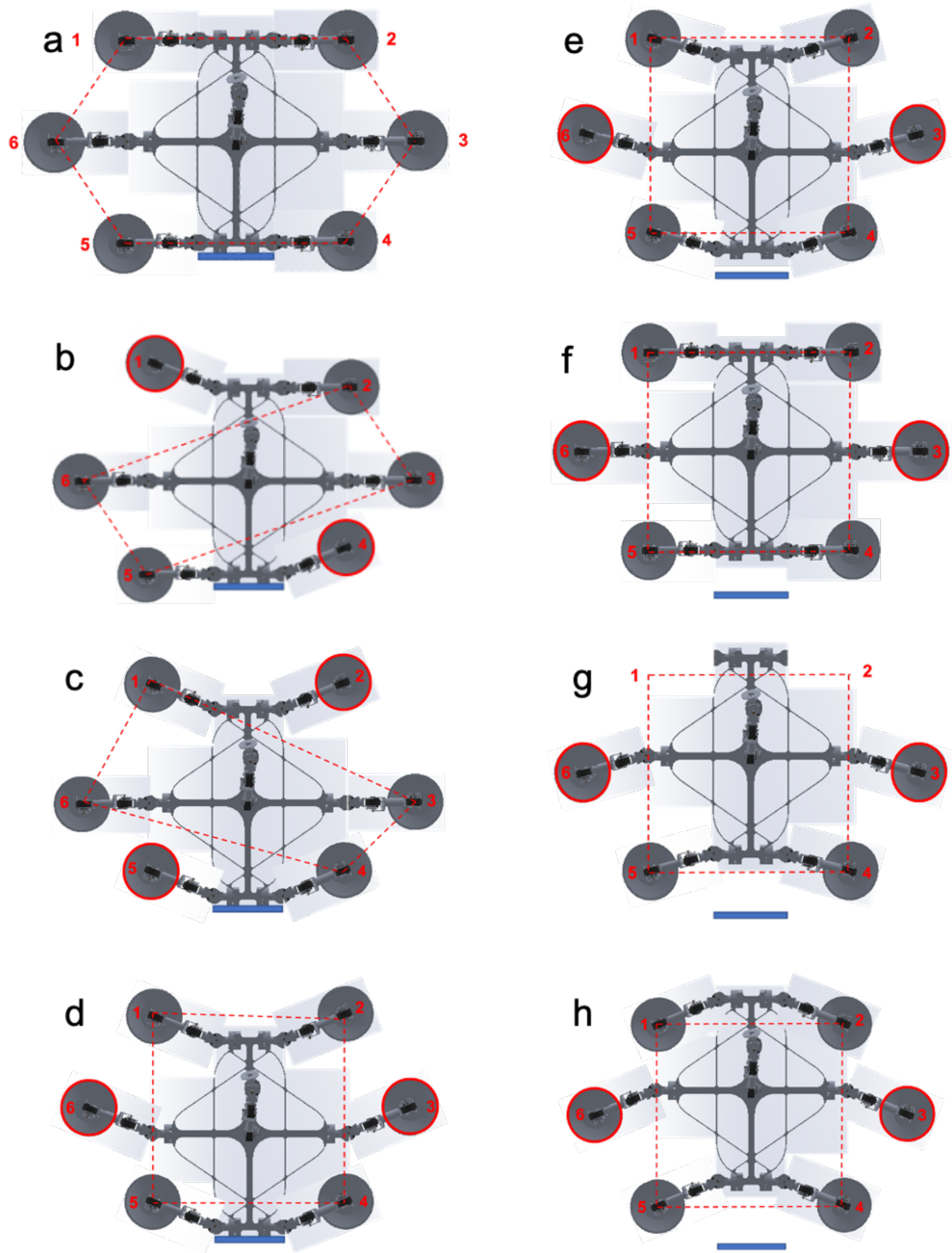



**Figure 14**: **The Magic Carpet gait: leg repositioning phase from (a) to (d), followed by pallet propulsion phase from (e) to (h). Unused shin tilt and pallet rotation degrees of freedom (total +4 DoF) will support complex walking over unstructured terrain.**

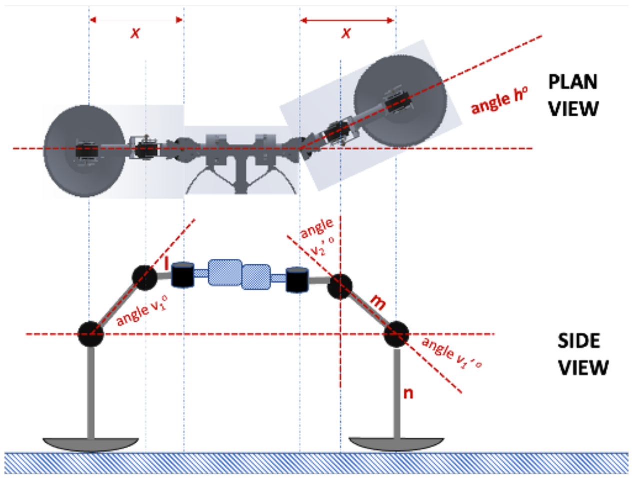



**Figure 15**: **Parameters $X$, $h$, $l$, $m$, $n$, $v_1$, and $v_2$ used in Magic Carpet walking gait.**

We expect the hip and elbow to output non zero torque while performing dynamic movements. Additionally, we expect actuator torques greater than those predicted due to dynamic movements. In the initial Gen 1 design, we accounted for these effects by designing for a high minimum continuous torque margin and a large peak torque rating (120 Nm) [17]. Actuator torque, measured during walking tests, will be used to correlate the predicted actuator torque with the actual actuator torque to yield more accurate predictions in future design iterations.

*Safer and more efficient variants of Magic Carpet gait*

Two additional variants of the proposed gait have been designed, providing operational flexibility depending on the terrain that is to be traversed on a specific mission.

The first variant is similar to the baseline Magic Carpet gait but the robot legs are in the 'inverted' position (see Figure 16a). The second variant (see Figure 16b) is inspired by a tortoise, when a tortoise shell (the Pallet) can be put on the ground between the leg movements. Note that for the inverted gait, only the side view is shown. For the tortoise gait, in the plan view, only the two front legs are shown. The main advantage of these variations is that the center of mass of the robot is lower than in the baseline gait which will improve robot stability while walking on steeper inclines.

*Simultaneous Optimization of two out of three Figures of Merit in tension: forward speed, torque margin, endurance*

Our custom tool provides comparisons between three competing Figures of Merit: forward speed measured in meters per second, actuator continuous torque margin (unitless), and endurance measured in meters of distance. These are optimized using goals and variables described in Table 2.

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. Subsequent Worm designs will be refined with a trade study of all three metrics to identify non-dominated architectures that efficiently allocate the robot's limited resources among forward speed, safety margin, and endurance.

**Table 2**: **Trade study metrics and the variables that optimize these metrics**

| 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 |

*Design optimization*

The optimization process was carried out in three steps, with the result of each step informing the decisions made in subsequent steps.

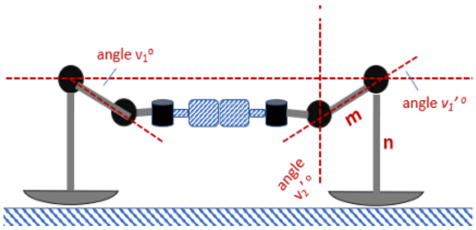
*Step One*—Preliminary exploration of the design space indicated that high hip swing angle and high fixed lateral distances are correlated with high forward speeds. Therefore, we set $X$ = 0.375m and full hip angle $h$ = 45 degrees and proceed to select limb lengths $l$ and $m$ to attain the fastest forward speed which still has $\sim$60% minimum torque margin. Higher $h$ would destabilize the robot uphill, while larger $X$ is infeasible to test due to lab space constraints.

*Result of step one*—From the tool output in Figures 18a, 18b and 19 we observe that, given $X$ = 0.375m and $h$ = 45 degrees on level ground, if we select $l$ = 0.25m and $m$ = 0.22m, then we'll be close, but not too close, to the feasibility frontier, with a predicted forward speed of $\sim$0.14 m/s and a predicted minimum torque margin for horizontal walking of $\sim$71%. Higher torque margins are unnecessary and sacrifice forward speed. Therefore, we fix the hardware parameters (limb lengths) of $l$ = 0.25m and $m$ = 0.22m and proceed to the next step, to explore optimal settings for software parameters under horizontal and inclined (30 degrees) walking.

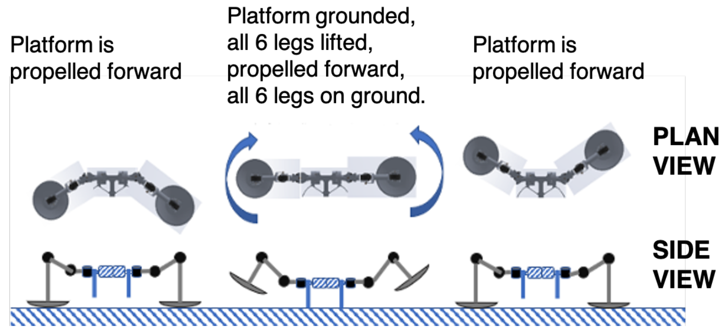
*Step two*—Given limb lengths of $l$ = 0.25m and for $m$ = 0.22m, we explore options for targeted fixed lateral distance $X$ and full hip angle $h$ for both horizontal and inclined walking with the same design principle: maximize forward speed subject to a minimum torque margin of $\sim$60%.

*Result of Step Two*—From the tool output in Figures 18c and 19, we observe that for inclined walking, with $X$ = 0.26m and $h$ = 37.5 degrees, we attain a forward speed of 0.07 m/s and a minimum torque margin of 65%. For horizontal walking, with $X$ = 0.375m and $h$ = 45, we attain a speed of 0.143 m/s and a minimum torque margin of 71%. It is important to iterate between steps 1 and 2 to approach the optimal design point that trades off forward speed with torque margin.

*Step Three*—Given limb lengths of $l$ = 0.25m and $m$ = 0.22m, and software parameters $X$ = 0.26m and $h$ = 37.5 degrees for inclined walking vs. $X$ = 0.375m and $h$ = 45 degrees for horizontal walking, we investigate the required minimum $v_1$ angles for each case to verify that the results comport with our physical intuition.




(a) Magic Carpet with inverted leg stance




(b) Magic Carpet with passive tortoise resting stance (not to scale)

**Figure 16**: **Variants of the Magic Carpet Gait.**

*Result of Step Three*—We observe that for inclined walking, where the targeted lateral distance $X$ = 0.26m is approximately the same as hip limb length $l$ = 0.25m, the minimum $v_1$ angle ends up being ∼83.6 degrees. This resembles "AT – AT" style walking where the limbs are brought in closer under the body, sacrificing forward speed for higher torque margins. For walking on level ground, where $X$ = 0.375m exceeds limb length $l$ = 0.25m, the minimum $v_1$ angle is about 45 degrees. This resembles faster, spider-style walking where the feet are planted further away from the body, sacrificing torque margins for higher speed. This is in accordance with intuition, as for any given RPM of the motors, if the feet are planted further out from the body, each leg swing goes further in the direction of travel, at the expense of longer moment arms and higher torque requirements.

*Final design points selected*—With software model inputs of $X$ = 0.26m, $h$ = 37.5 degrees, and hardware limb lengths of $l$ = 0.25m, $m$ = 0.22m, $n$ = 0.52m, we obtain a forward speed of 0.07 m/s and a minimum torque margin of 65% in the inclined case (30 degree incline). Using the same hardware limb lengths for the as-built robot, Figure 17, and changing only the software input parameters $X$ = 0.375m and $h$ = 45 degrees, we obtain a forward speed of 0.143 m/s and a minimum torque margin of 71% in the horizontal case (0 degrees incline).

*Endurance Modeling*

Endurance is not a driving requirement for Gen 1, however we calculated it after selecting the design point to see if it was an acceptable starting point for future generations. Future generations will be scaling up battery mass, so increasing endurance. The battery capacity of Gen 1 Worms is not a driving requirement. We could use an umbilical to power the WORMS-1 robot in the lab if testing revealed our selected battery does not provide sufficient walking distance. However, we later wanted to predict a hexapod's endurance to evaluate the Gen 1 Worm's design and predict the future performance of subsequent Worm generations. Power consumption ($P$) is back-calculated from the tool's actuator torques throughout the gait.

$$P = \frac{\tau V}{N K_T} \tag{3}$$

$$d_{end} = \frac{DoD Q_{bat}}{\int_0^T \frac{P}{V} dt} d_g \tag{4}$$

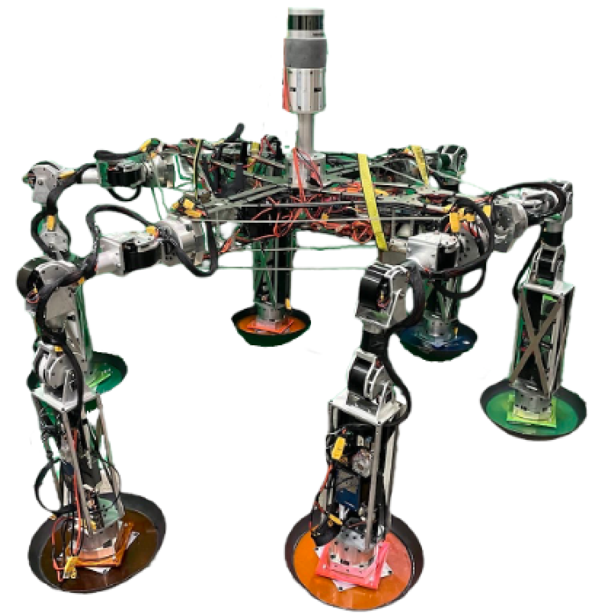


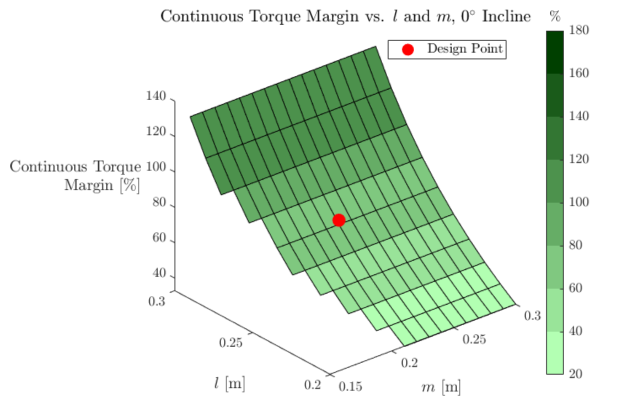
**Figure 17**: **The WORMS-1 robot as-built, Oct 2022.**

This model, described by Equation 3, assumes a constant actuator torque constant ($K_T$) and actuator supply voltage ($V$). Furthermore, robot endurance ($d_{end}$) is estimated using Equation 4. The gait motion is discretized in the Excel sheet, so the midpoint rule is used to approximate the integral. Note that $DoD$ is a Worm battery's max depth of discharge, $Q_{bat}$ is a Worm battery's capacity, $d_g$ is the distance traveled in a gait cycle, and $T$ is the gait cycle's period.

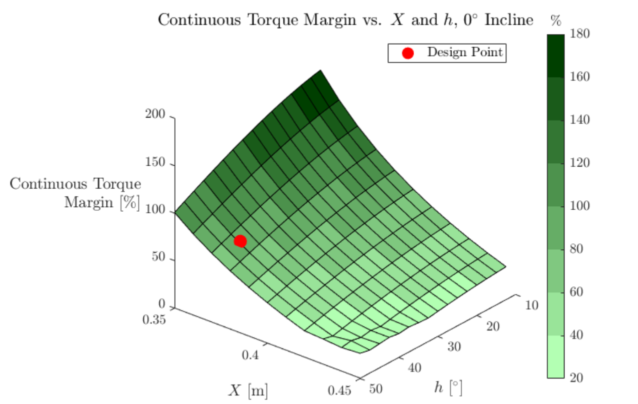
The AK80-64 actuator, used in the Gen 1 Worm, has a motor torque constant of 0.119 Nm / A, a gear ratio ($N$) of 64, and a rated voltage of 48 V [17]. Data from walking tests will be used to validate the torque, power, and endurance models.

*Predicting performance of future Worm Generations*

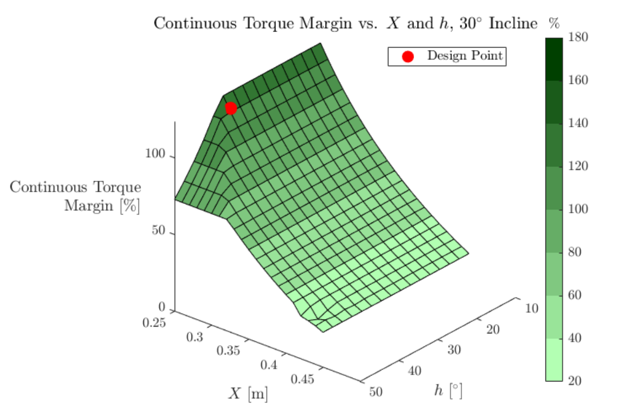
We also used this tool to predict the performance of future Worm generations. Several performance metrics, including minimum continuous torque margins and endurance, of three Worm generations are summarized in Table 3. This assumes that in subsequent Worm Generations, a single leg is moved at a time on inclines and that the Worm battery's maximum depth of discharge is 40%. Also, it is important to note




(a) Horizontal case with foot plant lateral distance $X$ = 0.375m and hip swing angle $h$ = 45 degrees




(b) Horizontal case with coxa length $l$ = 0.25m and thigh length $m$ = 0.22m




(c) Inclined case with coxa length $l$ = 0.25m and thigh length $m$ = 0.22m

**Figure 18**: **Minimum Continuous Torque Margins for horizontal and inclined cases with two software and two hardware parameters.**

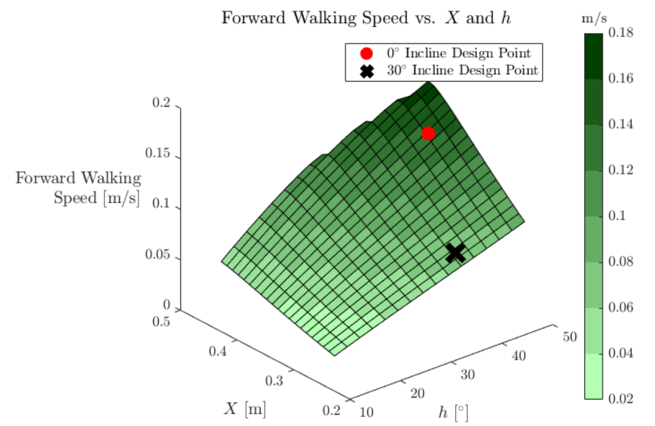



**Figure 19**: **Forward walking speed as a function of $X$, $h$ with $l$ = 0.25m and $m$ = 0.22m.**

that Gen 2 and Gen 3 endurance estimates are conservative because the Worms' actuators will feature brakes. These brakes will further reduce the actuators' power draw since motionless legs will resist gravity torques without using electrical power.

Gen 1 represents the current Worm design. Gen 2 Worms will feature more powerful actuators, such as the Harmonic Drive SHA-SG-25A-101 actuator, to carry more cargo while maintaining the same length ($\sim$1 m) as Gen 1 Worms [18]. Gen 3 Worms will use even higher power actuators, such as the Harmonic Drive SHA-SG-32A-161 actuator, to increase cargo capacity from kilograms to tons with a longer Worm length ($\sim$1.5 m) and higher Worm mass (60 kg) [15], [18]. These subsequent Worm generations employ higher power actuators and have different masses, so this tool is critical to understand how battery size must change to accommodate these larger power draws.

*Path to Flight: Predicting Performance on the Moon*

We used this trade study to form Gen 1 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 selected a coxa length ($l$) of 0.25 m and a thigh length ($m$) of 0.22 m 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 110kg.

## 7. Mechatronic Design and Testing

*Universal Interface Blocks*

Universal interface blocks (UIB), shown in Figure 6, are designed to mechanically and electrically connect the Worm with other WORMS components, such as the Pallet, Shoes, and Species Modules. For the ease of connection and disconnection of the UIBs, a cylindrical UIB body with

**Table 3**: **Summary of performance metrics of three Worm generations in lunar gravity for horizontal (H) and 30-degree inclined (I) cases, assuming a canonical hexapod form based on the WORMS-1 proof of concept.**

| | Gen 1 (H) | Gen 1 (I) | Gen 2 (H) | Gen 2 (I) | Gen 3 (H) | Gen 3 (I) |
|---|---|---|---|---|---|---|
| Minimum Continuous Torque Margin | 61% | 94% | 36% | 35% | 35% | 31% |
| Forward Walking Speed [m/s] | 0.143 | 0.07 | 0.069 | 0.025 | 0.054 | 0.012 |
| Endurance [m] | 438 | 127 | 388 | 51 | 1076 | 121 |
| Hexapod Payload Capacity [kg] | 400 | 400 | 900 | 900 | 1900 | 1900 |
| Robot Mass [kg/worm] | 10.1 | 10.1 | 20.4 | 20.4 | 58.6 | 58.6 |
| Robot Packed Volume [$m^3$] | 0.82 | 0.82 | | | | |

**Table 4**: **Selected Magic Carpet Gait Software Parameters and Predicted Performance for WORMS-1 Earth Demonstration and Lunar Mission.**

| Use Case | Ground incline [deg] | X [m] | h [deg] | Minimum Continuous Torque Margin | Walking Speed [m/s] |
|---|---|---|---|---|---|
| Earth, 0 kg payload | 0 | 0.375 | 45 | 75% | 0.143 |
| | 30 | 0.26 | 37.5 | 115% | 0.070 |
| Moon, 400 kg payload | 0 | 0.375 | 45 | 61% | 0.143 |
| | 30 | 0.26 | 37.5 | 94% | 0.070 |

androgynous interface and axially symmetric jaw connectors was employed. The number of jaw connectors was selected based on a trade-off between the machinability and structural strength. Internal space was reserved inside the UIB for mounting potential species modules. As bending from the Pallet is the most demanding loading case for the UIB connection, Finite Element Analysis (FEA) was performed to ensure a safety factor above 1.5 against the target bending load. Internal ribs were also created to mitigate buckling failure of the cylindrical thin wall structure. Eventually, the rigidity of the UIB connection was validated experimentally. For the Gen 1 Worm, power was transferred through external cables straddling across the UIBs for simplicity. However, in future Worm generations, the power connection will be integrated within the jaw connector for better reliability.

*Articulating Worms*

The Worm's limbs, Figure 10 and 13, were initially sized by modeling the hip structure, coxa, and thigh as cantilever beams and hollow shafts and the shin as an axially loaded column. A rectangular tube shape was selected for the shin due to its strength against buckling and simpler electrical packaging. The round tube shape was selected for the hip structure, coxa, and thigh due to its strength in bending in all directions and torsion. The failure criteria for bending beams, columns, and twisting shafts of these shapes are described by Equations 5, 6, 7, and 8 [19]. The buckling calculation is sensitive to the column's supports (variable C), so pinned-pinned ends (C = 1) were selected to be conservative.

$$FOS_{bend} = \frac{2I\sigma_{yield}}{(F_{app}L + M_{app})D} \tag{5}$$

$$FOS_{compress} = \frac{\sigma_{yield}A}{F_{app}} \tag{6}$$

$$FOS_{buckle} = \frac{C\pi^2 EI}{L^2 F_{app}} \tag{7}$$

$$FOS_{torsion} = \frac{2\tau_{all}J}{TD} \tag{8}$$

Instead of optimizing the robot's mass, we prioritized ease of manufacturing and assembly. For example, Equation 5 suggested that a 2in OD, $\frac{1}{8}$in wall thickness 6061-T6 tube would provide factors of safety to yield $> 6$ with 40% lower mass for the coxa tube. However, the thicker-walled tube provided enough material for M3 tapped holes within the wall, which reduced part count and simplified assembly.

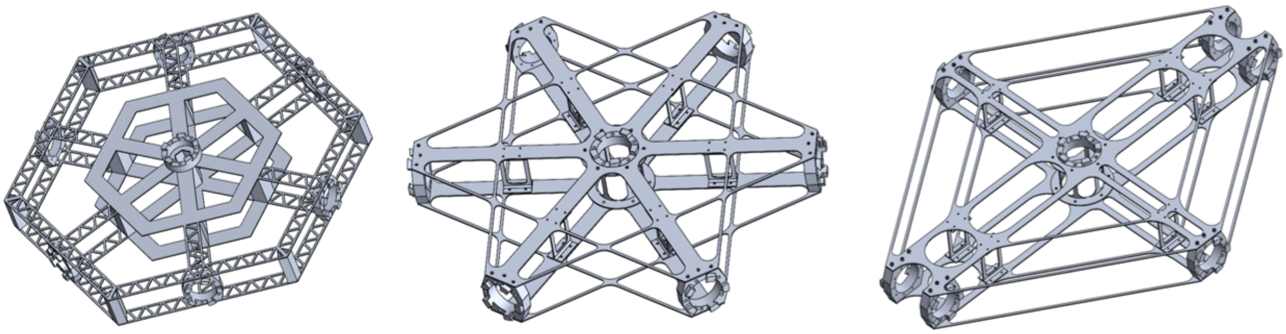


**Figure 20**: **Evolution of the double-layered pallet design.**

*Shoes*

The WORM shoes, Figure 9, were designed to be easily exchangeable and better adaptable to varying terrain. Depending on the environment, different shoe structures, sole tractions, etc. could be personalized. For the development of an example shoe, ideal requirements were created; the shoe should support walking on hard ground surface and soft "snow-like" regolith. Due to the gait mechanism, the shoe could not be greater than 14in in diameter so that it would not interfere with other legs, and could not exceed 3kg in mass.

*Pallet*

Three main functions of the pallet were to provide a body frame for the WORMS-1 hexapod, carry payload and provide a power bus for the worms to share power. These informed the following requirements throughout the design iterations shown in Figure 20.

1) The pallet shall include 6 UIBs for attaching 6 leg Worms and 1 additional UIB for attaching the 'neck' Worm with the 'Mapper' species module;

2) The relative location of the 6 UIBs for the leg Worms shall ensure that the legs do not interfere with each other during walking;

3) The pallet shall withstand loads and torques from the leg Worms in 1-g environment;

4) The pallet shall support the weight of the payload in 1-g environment; for WORMS-1, the payload includes the 'neck' Worm, a battery, power distribution boards, a router, the E-STOP switch, cable packs;

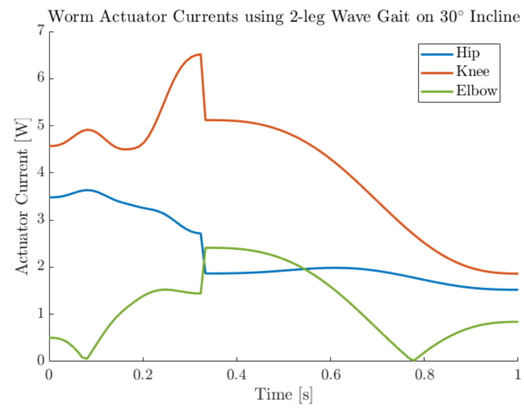
5) The pallet shall allow to easily attach and detach the payload elements, as well as ensure access to the latter when they are attached;

6) The mass of the pallet shall not exceed 8 kg.

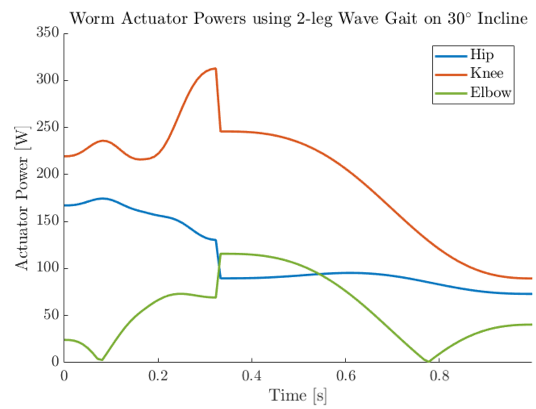
The main design-guiding principle was to reduce the pallet's mass while maintaining its structural strength against large loads and torques as well as ensuring that there is enough space between the Worm legs to support the walking gait.

*Electrical Design*

Using the Hexapod Actuation Calculator [16], we estimated power demand to size the power distribution system and the actuators according to peak demands as shown in Figure 21. In Gen 1, the electrical design has all the Worm batteries connected in parallel via the Pallet Main Power Bus, exchanging power using natural dynamics. The Gen 2 power distribution system envisages an active power flow controller that increases the WORMS feature-set.




(a) Joint currents over single leg gait motion




(b) Joint powers over single leg gait motion

**Figure 21**: **Joint currents and powers over single leg gait motion.**

## 8. Software Design and Testing

Given ROS 2's increased capability for multi-agent autonomy and cross computer communication, it was selected for use as the middleware that would support the software architecture for WORMS.

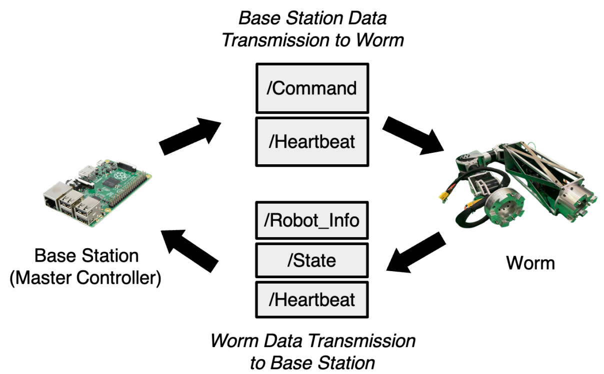



**Figure 22**: **ROS 2 Software Architecture.**

*WORMS Software Architecture*

The WORMS-1 proof-of-concept software architecture shown in Figure 22 is a centralized communication system with a single designated base Worm. Any cross-communication between Worms happens through the base Worm, which is responsible for both publishing commands and receiving responses. 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 Worm, which executes checkpoints and commands its children to act synchronously. In this way, the child Worm channels are not flooded with excess data from its sibling Worms. However, as the ROS 2 framework is flexible, different software architectures are possible.

*ROS 2 Message Structure*

All communications and operations are 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 "RobotInfo", "State", and "Heartbeat" which are all indicators of either nominal or un-anticipated performance.

*RobotInfo*—Contains crucial raw information about motor position, velocity, and torque for all actuators on the Worm.

*State*—Used as a numerical indicator of whether the Worm 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 the Worm.

## 9. Conclusions

Though equipped with technologies and built according to the system architecture that reflects this concept's end goal, WORMS-1 is ultimately a proof-of-concept prototype. Several design changes discussed below must take place before the system is ready for its first excursion on the lunar surface:

1) The most integral of those changes involves redesigning the Universal Interface Block. The UIB in WORMS-1 shows a realistic physical mating of different WORMS components. However, its locking mechanism merits revisions targeting improved reliability, longevity, and usability. Over time, some of the spring plungers that lock two UIBs into place experienced small deformations due to the shear stress imparted by the weight of components on a Worm. Ultimately, because of this deformation, using such a spring-loaded locking mechanism is a dangerous design choice that risks permanently locking two Worms together, even under the reduced gravitational loading of the Moon. An even more pressing revision to the UIB design concerns its ability to decouple. The current design exhibits a robust and easy-to-make physical connection between two Worms; decoupling two Worms, on the other hand, involves the use of five custom-made keys that push down every pair of pins in the interface. Such a cumbersome decoupling method is inadequate for lunar missions – it uses small, easy-to-lose parts that are relatively difficult to operate given the fact that extravehicular activity suits drastically reduce the manual dexterity of astronauts. A design principle akin to a Storz coupling, with levers that engage a locking mechanism, would be better suited at maintaining the original principle that lunar explorers should be capable of assembling and servicing Worms by hand out in the field. Finally, the next iteration of the UIB should integrate all power and data connections within the UIBs, allowing Worms to both physically and electromechanically couple without the need for external connections.

2) Another mechanical design change imperative to the architecture's flight readiness involves the motor wiring method. Due to the orientation of the actuators employed for the WORMS-1 technology demonstration, all wiring to the actuators was not only exposed but required unconventional bending and manipulation. This was mostly due to a limitation of the actuators used for the WORMS-1 architecture, which are by no means motors designed for activity on the lunar surface. However, for future iterations of the system, a wiring change and re-orientation of the motors such that there is no undue strain on electrical connections to the actuators, as well as running all cables and harnesses on the inside of a Worm's structural housing are critical.

3) As a prototype, WORMS-1 only exhibits a LIDAR species module. In future revisions, the WORMS architecture will employ a myriad of possible modules to expand the capabilities of different Worm robots.

4) Finally, the architecture as a whole must meet stringent considerations surrounding mechanical interfaces, thermal protection, radiation protection, vacuum exposure, and dust mitigation to fully meet the demands of any lunar mission.

In conclusion, we propose that WORMS is a resilient, easily maintainable, low-cost, evolvable, versatile, flexible, future-proof, and modular architecture for the rapid assembly of dozens of variants of extreme-terrain-access and specific-task-tailored heavy-duty robots that can support exploration and pioneering needs of NASA and its commercial and industrial partners throughout the Artemis program and on to Mars and beyond. The WORMS' architecture enables such operations as emplacement, assembly, inspection, maintenance, repair, parts swap, etc. which are necessary to pave the way for more mature planetary-surface logistics of the future. Those future architectures could then take advantage of roads and other traditional infrastructure to perform routine operations by faster and simpler wheeled vehicles. In this regard, the WORMS system can be considered as an important 'tip-of-the-spear' tool complementing and enabling more traditional systems.

## Appendix

**Table 5: Canonical Robot Forms Mapped to Use Cases.**

| | Elephants (Gen 1) | Goat & Ox (Gen 1 & Gen 2) | Spider (Gen 2 & Gen 3) | Mountain Climber (Gen 3) |
|---|---|---|---|---|
| **Installing Solar Panels** | Yes, it can carry heavy payloads. | Yes, optimized for this task | No | No |
| **Laying Cables** | Yes, with a winch accessory, it can lay cables as it travels. | Yes, optimized for this task. Lays cables as it climbs uphill. | Yes, it can be lowered into lava tubes with cables and lay wire in the lava tubes. | Yes, can lay cables across craters. |
| **Surveying Resources** | Yes, with added sensors. | Yes, with added sensors. | Yes, with added sensors. | Yes, with added sensors. |
| **Collecting Samples** | Yes, can carry payload. | Yes, can carry payload. | Yes, can carry payload. | Yes, can carry payload. |
| **Maintaining Infrastructure** | Yes, mainly bringing large payloads to needed areas. | Yes, mainly relaying information from surveying and bringing payloads to high peaks. | Yes, mainly relaying information from surveying and bringing payloads to lava tubes. | Yes, mainly relaying information from surveying and bringing payloads to/from areas with steep slopes. |
| **Constructing Habitats** | Yes, by bringing heavy payloads to necessary sites. | Yes, by bringing payloads such as construction materials to high ground. | Yes, by bringing payloads to lava tubes which the spider is optimized to travel to. | Yes, by bringing payloads to and from areas with steep slopes. |
| **Mapping Lava Tubes** | No | No | Yes, optimized for this task. | No |
| **Rescuing Astronauts** | Yes, can carry the weight of an astronaut for long distances. | No | Yes, may be able to pull an astronaut out of a lava tube with the same winching system used to pull up the WORMS walker from the lava tube. | No |

**Table 6**: **Canonical Robot Forms Mapped to Lifecycle Properties.**

| | **Elephants (Gen 1)** | **Goat & Ox (Gen 1 & Gen 2)** | **Spider (Gen 2 & Gen 3)** | **Mountain Climber (Gen 3)** |
|---|---|---|---|---|
| **Concept** | A train of mutually supporting Gen 1 walkers, similar to elephants that walk together trunk-to-tail in single file. This chain of walkers creates a long stable base on which heavy payloads may be distributed and allows for more stable climbing. | Two WORMS walkers, a Gen 2 "ox" and a Gen 1 "goat" tethered via a WORM with a winch. The skilled climber goes up the steep slope first, anchors itself and uses its winch to help the ox carry a heavy payload (such as a solar array) to the top. | Two WORMS walkers, a heavy Gen 3 carrier and a lightweight Gen 2 spider. The carrier anchors itself near the skylight rim. The spider is lowered into the lava tube on a winched rope to explore the lava tube, relaying data back to base via the carrier. | A Gen 3 WORM walker that drills into the top of a steeply-sloped crater to anchor itself and rappel down. At the bottom, it can detach, explore untethered, then pick up the rope again to pull itself up the steep slope, as mountain climbers do. |
| **Scalability** | Longer or shorter trains can be made with more or fewer worms. | Larger structures can be put together using more worms. | Larger Gen 3 WORMS robots can carry smaller Gen 2 robots. | Larger structures can be put together using more worms. |
| **Reusability** | The worms can be reused and reconfigured for other structures. | The drill anchor can be retracted and reused as well as the worms themselves. | Power cord can be retracted and the worms themselves can also be reused. | The drill anchor, winch can be retracted and reused (as can the worms). |
| **Simplicity** | Payload but no other accessories. | Extra moving parts such as winch, spool, and anchor. However, all of these are simple building blocks of the WORMS infrastructure. | Extra moving parts such as winch, spool, and anchor. However, all of these are simple building blocks of the WORMS infrastructure. | Extra moving parts such as winch, spool, and anchor. However, all of these are simple building blocks of the WORMS infrastructure. |
| **Flexibility** | Optimized for carrying large payloads but can also survey, explore, and travel long distances. | Optimized for climbing steep slopes but can carry payloads for long distances. | Many different use cases such as exploring lava tubes or craters. | Many different use cases such as going down craters or steep slopes as well as mapping the area. |
| **Reliability** | Long base with minimal accessories, can travel long distances reliably. They help each other through steep inclines. | Anchoring location is a failure mode. The location must be known to have hard ground instead of regolith. | Anchoring location is a failure mode. The location must be known to have hard ground instead of regolith. | Tethering back to a rope to climb out of a steep slope has risks such as improper attachment resulting in a fall. |
| **Durability** | The method of connection between the chain of walkers are other worms or pallet attachments which are both optimized for locking to other worms. Vulnerability to lunar dust. | The method of connection between the two walkers as well as the anchoring system - the accessories on the system - decide durability. Vulnerability to lunar dust. | The method of connection between the two walkers as well as the anchoring system - the accessories on the system - decide durability. Vulnerability to lunar dust. | Vulnerability to lunar dust, especially with moving parts when attaching back to the rope. |
| **Interoperability** | Two walkers working together to carry heavy payloads. Cables with power and data connect the two walkers. | Two walkers working together to carry heavy payloads. Cables with power and data connect the two walkers. | Two walkers working together to carry heavy payloads. Cables with power and data connect the two walkers. | Can release itself from winch rope and tether itself again once to pull itself out of a steep slope. |

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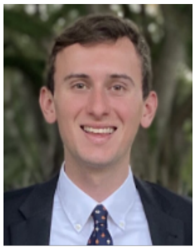

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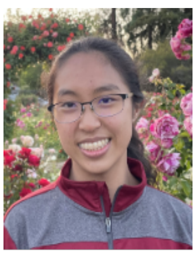

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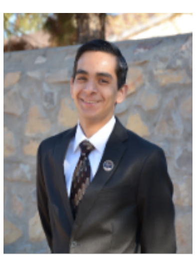

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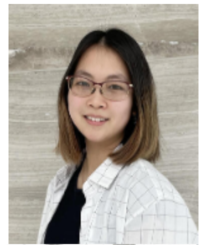

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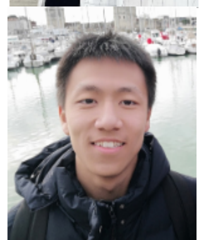

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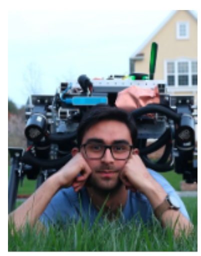

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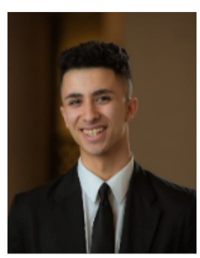

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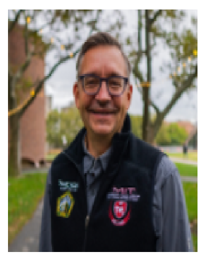

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