# Small Body Hopper Mobility Concepts

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**A propellant-saving hopper mobility system was studied that could help facilitate the exploration of small bodies such as Phobos for long-duration human missions. The NASA Evolvable Mars Campaign (EMC) has proposed a misson to the moons of Mars as a transitional step for eventual Mars surface exploration. While a Mars transit habitat would be parked in High-Mars Orbit (HMO), crew members would visit the surface of Phobos multiple times for up to 14 days duration (up to 50 days at a time with logistics support). This paper describes a small body surface mobility concept that is capable of transporting a small, two-person Pressurized Exploration Vehicle (PEV) cabin to various sites of interest in the low-gravity environment. Using stored kinetic energy between bounces, a propellant-saving hopper mobility system can release the energy to vector the vehicle away from the surface in a specified direction. Alternatively, the stored energy can be retained for later use while the vehicle is stationary in respect to the surface. The hopper actuation was modeled using a variety of launch velocities, and the hopper mobility was evaluated using NASA Exploration Systems Simulations (NExSyS) for transit between surface sites of interest. A hopper system with linear electromagnetic motors and mechanical spring actuators coupled with Control Moment Gyroscope (CMG) for attitude control will use renewable electrical power, resulting in a significant propellant savings.**

## Nomenclature

| | | |
|---|---|---|
| *ATHLETE* | = | All-Terrain Hex-Limbed Extra-Terrestrial Explorer robotic mobility system |
| *CMG* | = | Control Moment Gyroscope |
| *EAM* | = | Exploration Augmentation Module |
| *EMC* | = | NASA Evolvable Mars Campaign |
| *EVA* | = | Extra-Vehicular Activity |
| *HAL* | = | Habitable Air Lock |
| *LER* | = | Lunar Electric Rover |
| *NASA* | = | National Aeronautics and Space Administration |
| *NExSyS* | = | NASA Exploration Systems Simulations |

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| | | |
|---|---|---|
| *PEV* | = | Pressurized Exploration Vehicle, Pressurized Excursion Vehicle |
| *RCS* | = | Reaction Control System |
| *SPE* | = | Solar Proton Event |
| *SPR* | = | Small Pressurized Rover |

## I. Introduction

THE NASA Evolvable Mars Campaign (EMC) is evaluating a variety of step-wise missions to eventually allow for the human exploration and pioneering of the surface of Mars (Crusan 2014). Exploration of the Mars system will require vehicles and mobility systems for extreme environments that include microgravity, low and variable gravity, and Mars gravity. A hardware approach that emphasizes commonality is intended to use a similar vehicle cabin with modular mobility systems appropriate for the target environment. Previous development work on a small crew cabin include Small Pressurized Rover (SPR), Lunar Electric Rover (LER), and Habitable Air Lock (HAL) (Abercromby, et al, 2015). The most advanced embodyment of the small crew cabin is the Pressurized Exploration Vehicle (PEV).

Small bodies include asteroids, comet cores, and smaller moons such as Phobos and Deimos (Wallace, et al 2012) in the Mars system. The small body environment is characterized by low and variable gravity that reduces the effectiveness of wheels, tracks, limbs, and other mobility concepts that depend on friction. The challenge in this study was to develop a concept for small body environments that will join the repertoire of modular mobility systems designed to carry the PEV between various surface destinations.

## II. Pressurized Exploration Vehicle (PEV)

The PEV concept is an evolution of the lunar electric rover concept developed for lunar surface habitation and exploration during the Constellation program (Chappell, Abercromby & Gernhardt, Aug 2013; Chappell, Abercromby, Reagan, Gernhardt 2013; Abercromby, Gernhardt & Litaker 2010; Abercromby, Gernhardt & Jadwick 2012; Abercromby, Gernhardt & Litaker 2012; Abercromby, Gernhardt, Conkin 2013; Gernhardt & Abercromby 2008), and which was more recently adapted and evaluated for exploration of near-Earth asteroids (Abercromby, Chappell, Litaker, Reagan & Gernhardt 2013; Abercromby, Chappell & Gernhardt, Oct 2013; Litaker, et al nd) and Phobos (Abercromby, et al, 2015). The PEV concept consists of a core cabin that can be kitted with work packages and mobility systems depending on mission needs. The PEV core cabin is nominally sized to accommodate 2 crewmembers for up to 14 days or up to 50 days if augmented with a pair of inflatable logistics modules. Rapid EVA egress and ingress is enabled via 2 suit ports and an exploration atmosphere of 56.5 kPa (8.2 psi), 34% $O_2$, 66% $N_2$ (Abercromby, Gernhardt & Conkin 2013). The ability to rapidly egress and ingress the vehicle is assumed to enable single-person EVAs in the vicinity of the PEV, with contingency rescue capability being provided by the PEV pilot (Abercromby, Chappell, Litaker, Reagan & Gernhardt 2013; Abercromby, Chappell & Gernhardt 2013). Thermal control is maintained using a radiator combined with a water-filled fusible heat sink, which also functions as protection against Solar Proton Event (SPE) radiation.

For operations on and near Phobos the PEV would use a reaction control system (RCS) sled mounted to the cabin. In this study, the RCS sled provided 200 m/s of Delta-V using hydrazine ($N_2H_4$) propulsion (Isp = 225 s) with refueling capability. The RCS sled could potentially be augmented with a mechanical propulsion system, referred to as a "hopper", which would use electromechanical actuators to propel the PEV vertically and possibly horizontally to reduce the consumption of propellant required for Phobos surface exploration..

A robotic arm with a foot restraint, referred to collectively as an astronaut positioning system (APS), would be mounted to the front of the vehicle to provide a work platform for an EVA astronaut (Figure 8). Data from multiple test environments has shown an APS to be the only totally acceptable way to perform all tested exploration tasks due to the stabilization that it provides coupled with ability to translate with multiple payloads and scientific samples (Abercromby, Chappell, Litaker, Reagan & Gernhardt 2013; Chappell, Abercromby & Gernhardt 2013; Chappell, Abercromby, Reagan & Gernhardt 2013). The infrequent need to recharge or resupply coupled with the SPE protection and pressurized safe-haven that the PEV provides means that exploration range of any single PEV excursion is limited primarily by the availability of an alternate safe haven in the event that the PEV becomes immobilized or suffers another significant failure. This contingency rescue capability could be provided by a second PEV-class vehicle (as in the lunar conops (Abercromby, Gernhardt & Jadwick 2012)) or it could be provided by a crew taxi, mobile habitat, or possibly combined with EVA jetpacks.

Consistent with PEV operational assumptions for near-Earth asteroids (Abercromby, Chappell, Litaker, Reagan & Gernhardt 2013; Abercromby, Chappell & Gernhardt 2013), assumed maximum translation rates were 0.1 m/s (~0.3 ft/s) when < 5 m from the surface and 0.6 m/s (~2 ft/s) when > 5 m from the surface; assumed nominal rate

was 0.3 m/s (~1 ft/s). Assumed sample and equipment payload capacity was 454 kg (~1,000 lb) and 1.0 m3 (~35 $ft^3$).

The PEV was assumed to land on the Phobos surface before performing each exploration task. The mass of the PEV, estimated at 7,689 kg (dry, including hopper) for the Phobos configuration, was assumed to be adequate to provide reaction forces to allow exploration tasks to be performed without anchoring or constant thrusting. At the time of writing, analysis is being performed to quantify the force profiles and corresponding RCS and / or control moment gyroscope reactions that would be required to enable acceptable performance of EVA exploration tasks.

A potential limitation of the PEV concept as evaluated is that propellant mass calculations assume Hydrazine as the propellant. Although the extension of the EVA astronaut in front of the PEV would reduce potential pluming in the immediate vicinity of EVA task locations, it is possible that contamination could result. The ability to mechanically translate and brake using a hopper could reduce or eliminate possible contamination.

## III. Modular Systems and Commonality Studies

NASA Evolvable Mars Campaign (EMC) studies have recommended that missions refrain from a proliferation of multiple, unique habitable volumes and vehicle cabin sizes and types (Howe, et al 2015). Ideally, a single large volume habitat type and single small cabin type would be preferable. Using a single small cabin type, a variety of equipment, mobility systems, and outfitting can be attached for various mission functions and purposes (Figure 1).

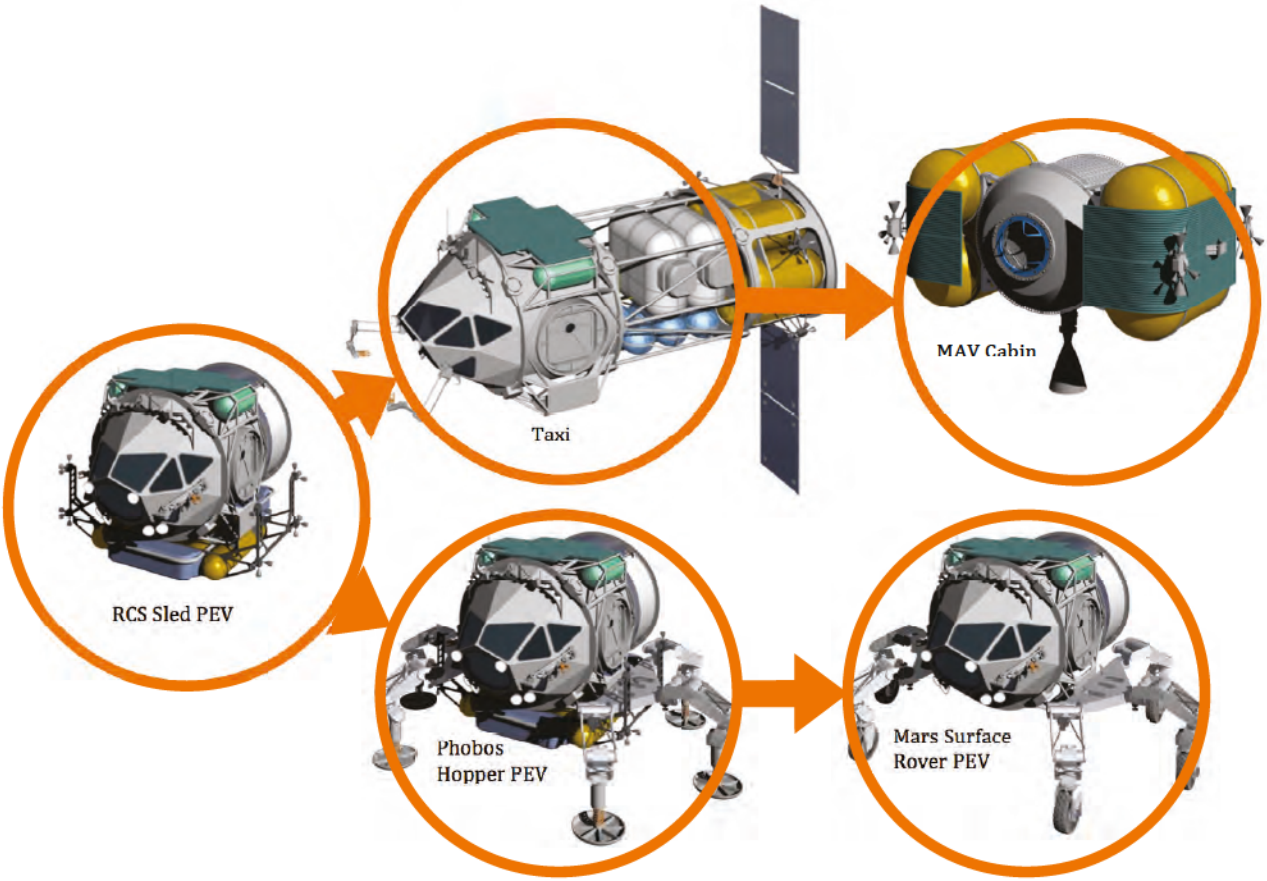



**Figure 1: In-space and surface mobility commonality – small cabins can be fitted with a variety of in-space propulsion or surface mobility systems**

As has been discussed above, the PEV small rover / vehicle concept has produced a significant body of research in regard to cabin size, volume, and function, and exists as a leading starting point for small cabin research toward a standard common size. Howe (2015) explored a range of habitable outposts, habitats, and vehicle cabins based on a fixed small diameter. Further research under the EMC has expanded on commonality in small cabins, in an ongoing effort to find a minimal common cabin that meets the PEV needs, yet also is applicable to other cabins for rovers, hoppers, Exploration Augmentation Modules (EAM), space logistics modules, surface logistics modules, space taxis, RCS sleds, Mars Ascent Vehicle (MAV) cabins, etc (Griffin, et al 2015). The Small Body Hopper Concept

assumes a common cabin that can be used in a variety of environments (zero-g, variable gravity, Mars surface, etc) with appropriate mobility systems for the target environment. The same PEV cabin can be fitted with wheeled mobility systems for Mars surface, and a hopper system has been devised that is appropriate for small bodies.

## IV. Small Body Hopper Concept

With low gravity small bodies, wheeled mobility has reduced or negligible utility due to a lack of traction and friction. Small bodies such as Mars' moons Phobos or Deimos have enough gravity that "docking", navigation, and proximity operations begin to consume significant quantities of propellant compared to spacecraft-to-spacecraft in-space proximity operations. Gravity acceleration on these bodies have enough potential energy at altitude to capitalize and capture in a hopper-type mechanism, for rhythmic mobility similar to a person on a "pogo stick". The small body hopper concept uses springs to store energy as the PEV falls back to the surface, and selectively releases the energy to save propellant. Two hopper mobility systems were explored -- a four-legged spring-loaded truss concept, and a six-limbed concept based on Jet Propulsion Laboratory's All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system.

### A. Hopper Actuation

The small body hopper will use actuated springs – the spring can be compressed passively due to impact or actively due to an electrically powered actuator. A mechanical ratchet mechanism can keep the spring compressed until the ratchet is released. Kinetic energy during descent to the Phobos surface is conserved when the springs are compressed on impact, converting to potential energy in the spring. The potential energy stored in the spring can either be immediately released in a "hop", partially or controlled released to "hop" in a specified direction, or ratcheted down to be released later. Losses occur in friction due to buckling, actuator mechanism, and some losses during impact. These losses can be recuperated each time the hopper impacts the ground by adding to the spring compression through actuator electrical current. Release of the compressed spring thrusts the vehicle upward and converts to kinetic energy and gravitational potential energy. Thrusters can prolong or direct the "hop" motion until kinetic energy reaches zero at the highest altitude and gravitational potential energy is at its peak, whereupon the hopper falls to the surface again and the "hop" cycle repeats.

### B. Spring-loaded Truss Hopper Mobility Concept

A four-legged spring-loaded truss design explored lightweight wide-stance trusses with footpads (Figure 2). With the "cocked" or loaded configuration set at zero, spring trusses can extend 1.13m as the springs are released (Figure 3). The "cocked" configuration is shown in Figure 4, left, with relaxed configuration in Figure 4, right.

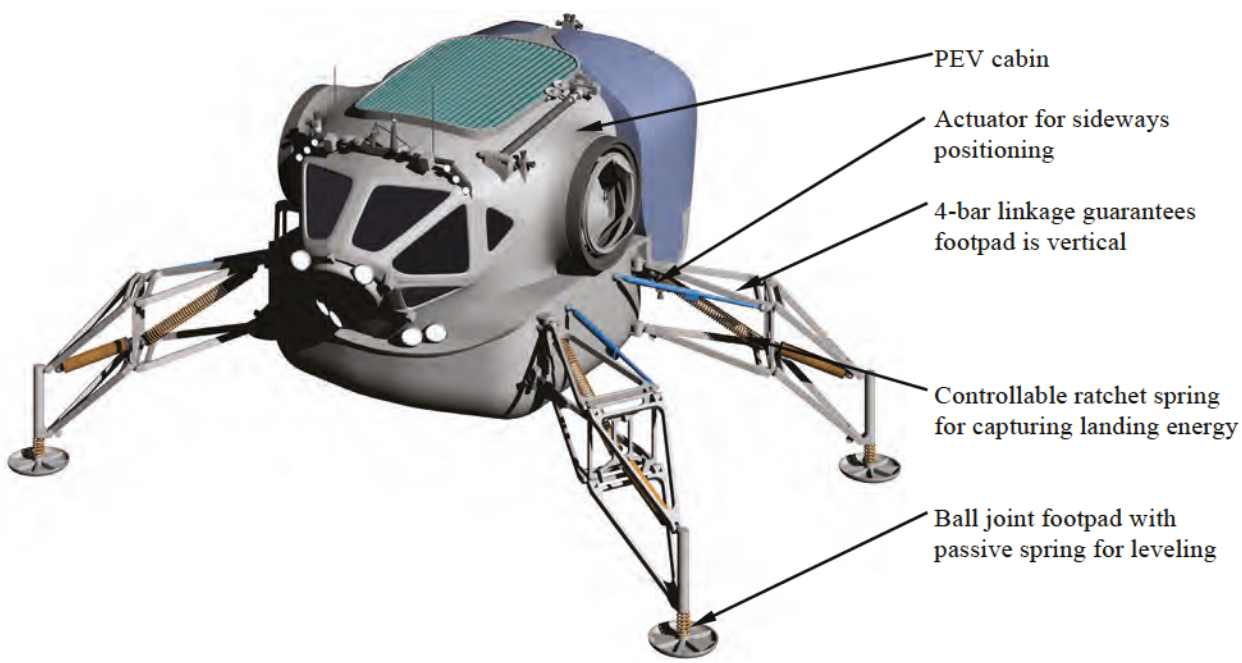



**Figure 2: Spring-loaded Truss Phobos hopper**

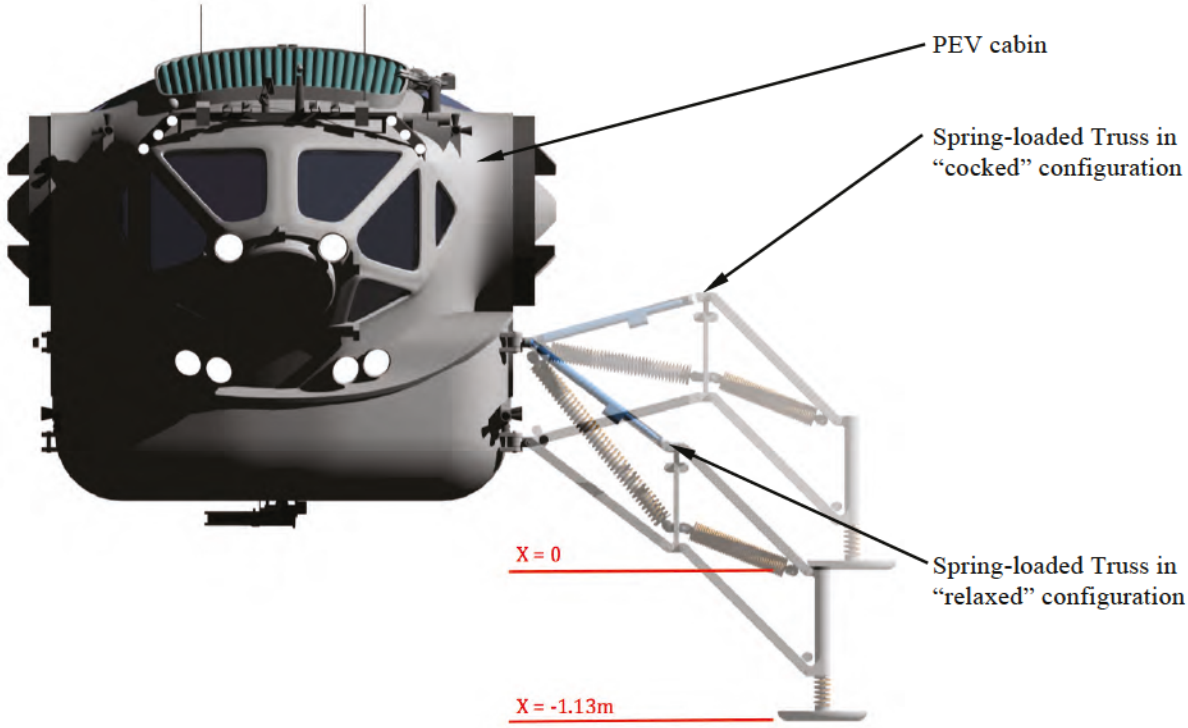



**Figure 3: Spring-loaded Truss Phobos hopper leg range**

Masses for each leg are shown in Table 1. Each truss leg is estimated to be a little over 350kg, but with further development the mass could be reduced. Launch velocities were evaluated at 0.58m/s and 1.51m/s. Parameters for 1.51m/s are shown in Table 2, and four leg loading cases are shown in Table 3, resulting in a maximum leap height of 202.38m above the surface.

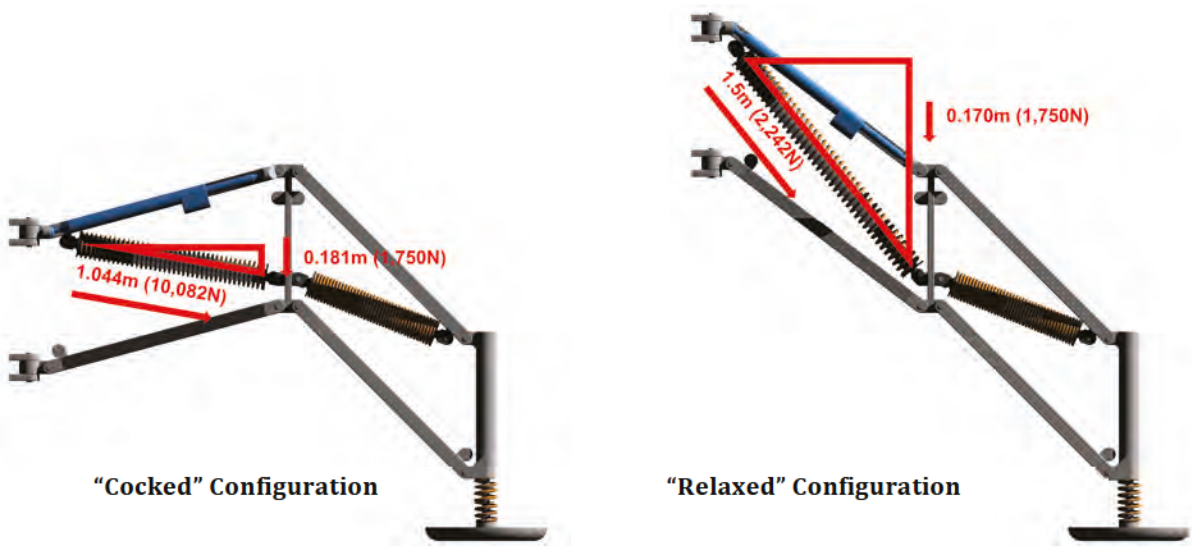



**Figure 4: Spring-loaded Truss force diagrams**

**Table 1: Spring-loaded Truss masses for each leg**

| Spring-loaded Truss MEL | (kg) | qty | |
|---|---|---|---|
| Pivot mount | 2.7 | 2 | 5.40 |
| Wishbone | 32.2 | 4 | 128.80 |
| Square frame | 30 | 1 | 30.00 |
| Footpad cylinder | 24.5 | 1 | 24.50 |
| Footpad shaft | 3.6 | 1 | 3.60 |
| Footpad spring | 1 | 1 | 1.00 |
| Footpad | 23 | 1 | 23.00 |
| Actuator cylinder | 8.5 | 1 | 8.50 |
| Actuator piston | 4 | 1 | 4.00 |
| Pin | 0.4 | 4 | 1.60 |
| Spring actuator | 42.9 | 2 | 85.80 |
| Main spring | 18.28 | 2 | 36.56 |
| **Total / leg** | | | **352.76** |
| **Total suspension system** | | **4** | **1411.04** |

**Table 2: Spring-loaded Truss parameters for launch velocity 1.51m/s**

| **Velocity (m/s) =** | **1.51** |
|---|---|
| Spring | |
| End Type = | closed & ground |
| Free Length (m) = | 1.5 |
| Outer Dia (m) = | 0.15 |
| Wire Dia (m) = | 0.02 |
| Active Coils = | 38 |
| Material = | Stainless 17-7 A313 |
| Spring Const k (N/m) = | 18130 |
| Spring Mass (kg) = | 41.06 |
| Max Travel (m) = | 0.7 |

The test case uses Phobos gravity of $0.0057 m/s^2$, which is rounded up to $0.01 m/s^2$ in Table 3 and Table 8. Variations of the equation $E = 1/2Mv^2 + 1/2kx^2 + MGx$ is used in all four cases where:

k = Spring constant
k(eq) = Spring constant equivalent (taking into account diagonal spring)
G = Gravity of Phobos
M = Mass of hopper divided by number of legs
E = Energy per leg
v = Vertical speed
x = Vertical displacement; Case A x value is ground elevation

**Table 3: Four loading cases for Spring-loaded Truss legs at 1.51m/s launch velocity**

| Case A: "cocked" | | | Case B: "relaxed" just leaving surface | | | Case C: "relaxed" top of bounce | | | Case D (B check): kinetic E at maximum | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| k = | 18130.00 | N/m | k = | 18130.00 | N/m | k = | 18130.00 | N/m | k = | 18130.00 | N/m |
| k(eq) = | 3147.09 | N/m | k(eq) = | 14151.19 | N/m | k(eq) = | 14151.19 | N/m | k(eq) = | 14151.19 | N/m |
| G = | 0.01 | m/s2 | G = | 0.01 | m/s2 | G = | 0.01 | m/s2 | G = | 0.01 | m/s2 |
| M = | 1750.00 | kg | M = | 1750.00 | kg | M = | 1750.00 | kg | M = | 1750.00 | kg |
| E = | 2007.47 | J | E = | 2007.47 | J | E = | 2007.47 | J | E = | 2007.47 | J |
| v = | 0.00 | m/s | v = | 1.51 | m/s | v = | 0.00 | m/s | v = | 1.51 | m/s |
| x = | -1.13 | m | x = | 0.00 | m | x = | 201.25 | m | x = | 0.00 | m |
| E = | 2007.47 | | | | | **202.38** | **m above surface** | | | | |

## C. ATHLETE-based Hopper Mobility Concept

Whereas the spring-loaded truss design has many unknowns such as structure mass, a second hopper mobility concept was studied based on the well-known All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system, for which working prototypes exist (Wilcox 2012; Wilcox, et al, 2007). The ATHLETE is a six-limbed mobility platform originally designed as an articulated wheeled mobility system. Each of the six limbs has a tool adapter at the hub of the wheel that takes advantage of the wheel motor to open and close manipulators, turn drills and augers, or any other number of mechanical local tasks. Eventually the wheels also became tool

attachments, where the default six-limbed system is capable of swapping wheels, drills, manipulators, low-gravity anchors, and hopper mechanisms in any environment from zero-g through partial and full gravities. The current ATHLETE limb concept is well-suited for a Phobos mobility system with spring-loaded footpads because an identical ATHLETE mobility system fitted with wheels can also be used on the Mars surface.

**Table 4: Estimated ATHLETE vs payload mass in Phobos gravity**

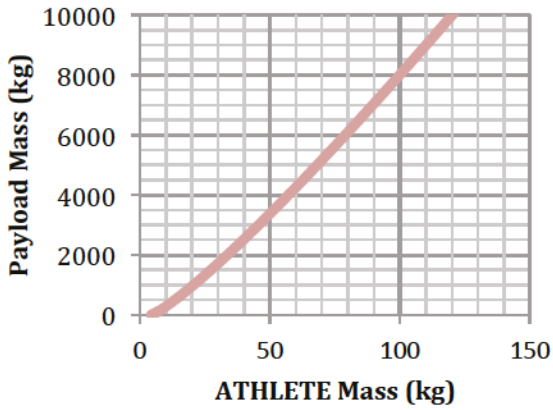
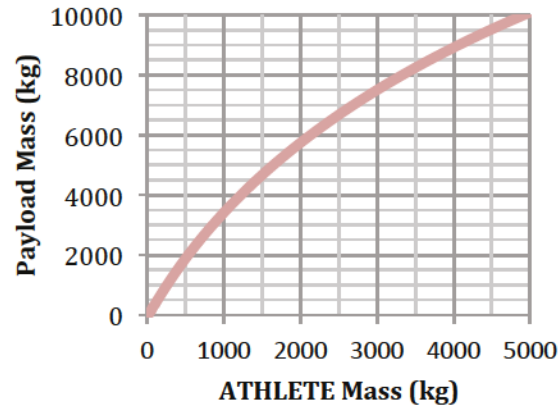



**Table 5: Estimated ATHLETE vs payload mass in Mars gravity**



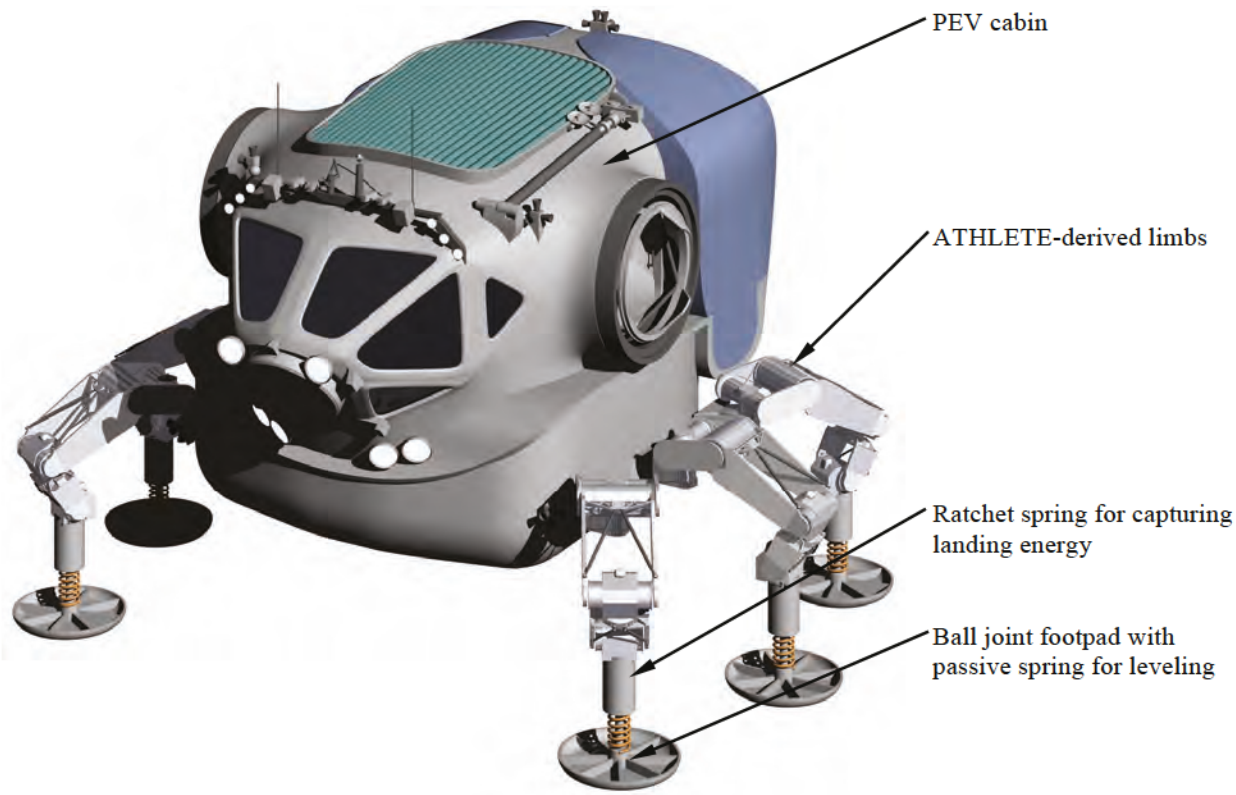




**Figure 5: ATHLETE-derived hopper**

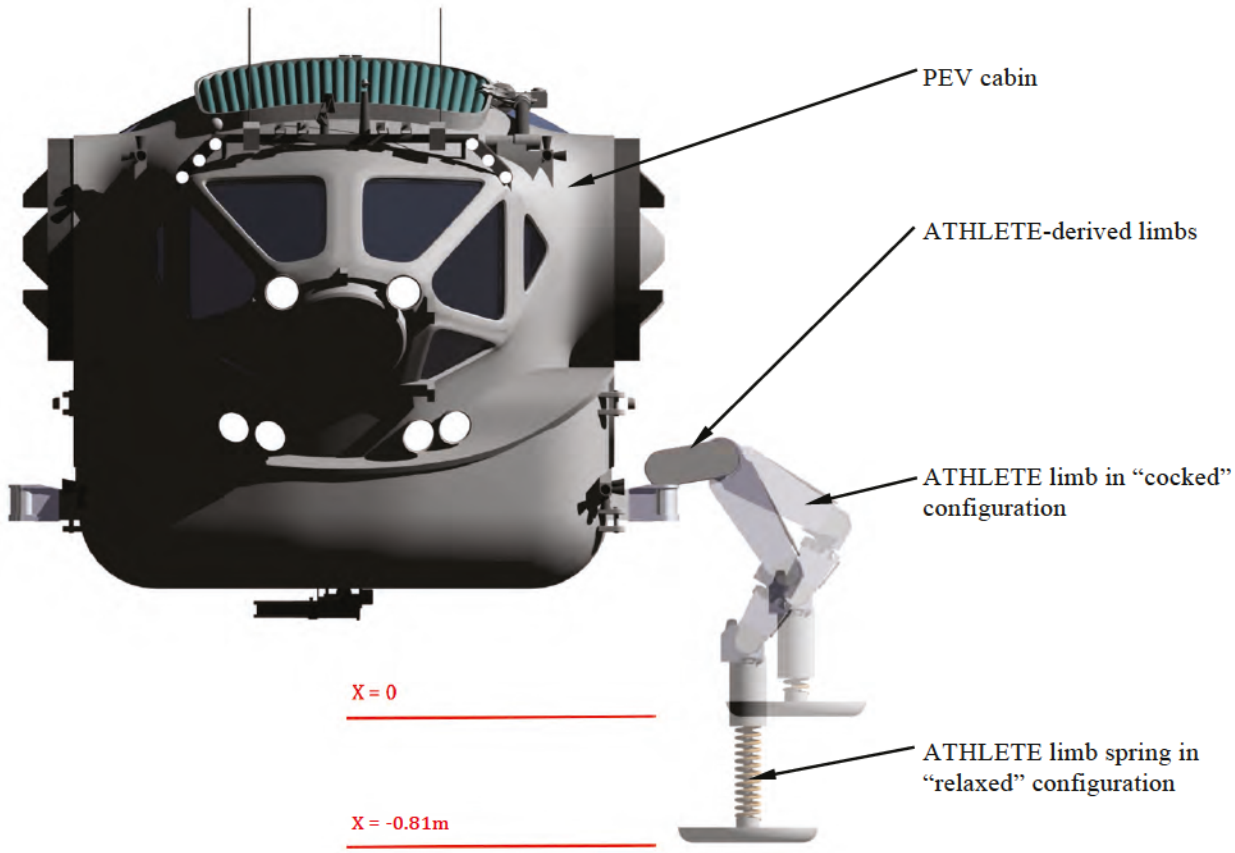



**Figure 6: ATHLETE-derived hopper leg range**

At the heart of the ATHLETE concept is the limb, which is repeated six times around the body of the robot (Heverly, et al 2010). Each multi-link limb is a six or seven degree-of-freedom (DOF) robotic arm (depending on the number of modular links that have been attached to the chain), consisting of rotary actuators at each joint and lightweight aluminum links between the joints. Each joint consists of an electric motor mated to a high-reduction planetary gearbox and harmonic drive, which provides high torque capability and excellent precision. The torque on each joint is measured and together with the known stiffness of the limb can be used to approximate the true position of the end effector. Each limb has a general-purpose tool adapter at its tip that allows robotic change-out of tools such as scoops, augers, grippers, or other hardware. The general-purpose tool adapter can also accommodate mobility wheels for Mars surface, or spring mechanisms for small body hopper mobility.

ATHLETE's onboard software provides coordinated joint motion, including cartesian positioning of limb end effectors and wheels. Waypoints are used to achieve straight-line paths between cartesian locations. Motions of multiple limbs are also coordinated to enable body positioning. When two Tri-ATHLETEs are docked to a cargo pallet, they operate in a master-slave mode, in which motion of all six limbs is coordinated by the master platform.

The ATHLETE platform is designed to accommodate a variety of operating paradigms (Townsend & Mittman 2012). For Lunar missions, ATHLETE would be controlled primarily via remote teleoperation from Earth. The ATHLETE robot is teleoperated via a workstation that has both a command uplink and video/telemetry downlink from the robot. A remote operator would maintain good situational awareness through the use of state displays and stereo imagery streamed from ATHLETE's onboard cameras, and would control ATHLETE using computer interfaces or handheld physical controllers tailored to the current task. This philosophy of remote teleoperation could also be implemented for use by an astronaut onboard a Mars or lunar orbiting spacecraft or inside a Mars or lunar surface habitat. Astronauts deployed alongside the ATHLETE platform could operate the robot via local on-site control, making use of gesture recognition or handheld physical interfaces similar to those used by the teleoperators. This function works well with crew riding in the PEV cabin, where local control can operate an ATHLETE-based hopper moblity system for precision directional jumping.

An ATHLETE-derived hopper system with permanent, fixed legs is shown in Figure 5, with spring mechanisms and foot pads mounted to ATHLETE limbs as modular tool attachments. Masses for each leg (based on the current

prototype) are shown in Table 6. However, these masses can be optimized for various conditions and loadings. For example, a rough estimate for an ATHLETE system optimized for Phobos to carry a 5,000kg payload would only have a total mass of 70kg, or about 12kg per leg (Table 4). Alternatively, carrying 5,000kg on Mars surface would roughly need a 1,650kg ATHLETE, or about 275kg per leg (Table 5). Therefore the current prototype ATHLETE at 244kg per leg is closer to a proposed multi-environment 5,000kg payoad carrier that could both be used on Mars or Phobos, even though the design for the latter environment might be greatly exceeded.

In this design, a "cocked" or loaded ATHLETE-derived spring hopper mechanism can extend 0.81m as the springs are released (Figure 6), and has an added advantage of being able to use limb joint motors for subtle articulation in navigation, motion, and spring mechanism handling. Launch velocities were evaluated at 0.53m/s and 1.56m/s. Parameters for 1.56m/s are shown in Table 7, and four leg loading cases are shown in Table 8, resulting in a maximum leap height of 213.15m above the surface. Alternative designs for the hopper included detachable Tri-ATHLETE three-limb vehicles that can dock to either side of a payload (Figure 7), providing a flexible method for hopper mobility on a small body, while at the same time keeping the ATHLETE handy for mobile propellant factory, large-scale 3D printing (Howe, et al 2013; Howe, et al 2014), paving, or other construction tasks.

**Table 6: ATHLETE-based masses for each leg**

| ATHLETE-derived leg MEL | (kg) | qty | |
|---|---|---|---|
| Hip yaw | 20.8 | 1 | 20.80 |
| Hip pitch | 24.4 | 1 | 24.40 |
| Lower thigh | 4.6 | 1 | 4.60 |
| Knee pitch | 16.4 | 1 | 16.40 |
| Knee roll | 13.8 | 1 | 13.80 |
| Shin | 1.8 | 1 | 1.80 |
| Ankle pitch | 11.2 | 1 | 11.20 |
| Ankle roll | 13.6 | 1 | 13.60 |
| FT sensor | 10 | 1 | 10.00 |
| Footpad cylinder | 55 | 1 | 55.00 |
| Footpad shaft | 3.6 | 1 | 3.60 |
| Footpad spring | 2 | 1 | 2.00 |
| Footpad | 23 | 1 | 23.00 |
| Avionics | 43.3 | 1 | 43.33 |
| **Total / leg** | | | **243.53** |
| **Total suspension system** | | **6** | **1461.20** |

**Table 7: ATHLETE-based leg parameters for launch velocity 1.56m/s**

| | |
|---|---|
| **Velocity (m/s) =** | **1.56** |
| Spring | |
| End Type = | closed & ground |
| Free Length (m) = | 0.5 |
| Outer Dia (m) = | 0.15 |
| Wire Dia (m) = | 0.01 |
| Active Coils = | 8 |
| Material = | Stainless 17-7 A313 |
| Spring Const k (N/m) = | 4309 |
| Spring Mass (kg) = | 2.76 |
| Max Travel (m) = | 0.4 |

**Table 8: Four loading cases for ATHLETE-based legs at 1.56m/s launch velocity**

| Case A: "cocked" | | | Case B: "relaxed" just leaving surface | | | Case C: "relaxed" top of bounce | | | Case D (B check): kinetic E at maximum | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| k = | 4309.00 | N/m | k = | 4309.00 | N/m | k = | 4309.00 | N/m | k = | 4309.00 | N/m |
| k(eq) = | 4309.00 | N/m | k(eq) = | 4309.00 | N/m | k(eq) = | 4309.00 | N/m | k(eq) = | 4309.00 | N/m |
| G = | 0.01 | m/s2 | G = | 0.01 | m/s2 | G = | 0.01 | m/s2 | G = | 0.01 | m/s2 |
| M = | 1166.67 | kg | M = | 1166.67 | kg | M = | 1166.67 | kg | M = | 1166.67 | kg |
| E = | 1412.09 | J | E = | 1412.09 | J | E = | 1412.09 | J | E = | 1412.09 | J |
| v = | 0.00 | m/s | v = | 1.56 | m/s | v = | 0.00 | m/s | v = | 1.56 | m/s |
| x = | -0.81 | m | x = | 0.00 | m | x = | 212.34 | m | x = | 0.00 | m |
| E = | 1412.09 | | | | | **213.15** | **m above surface** | | | | |

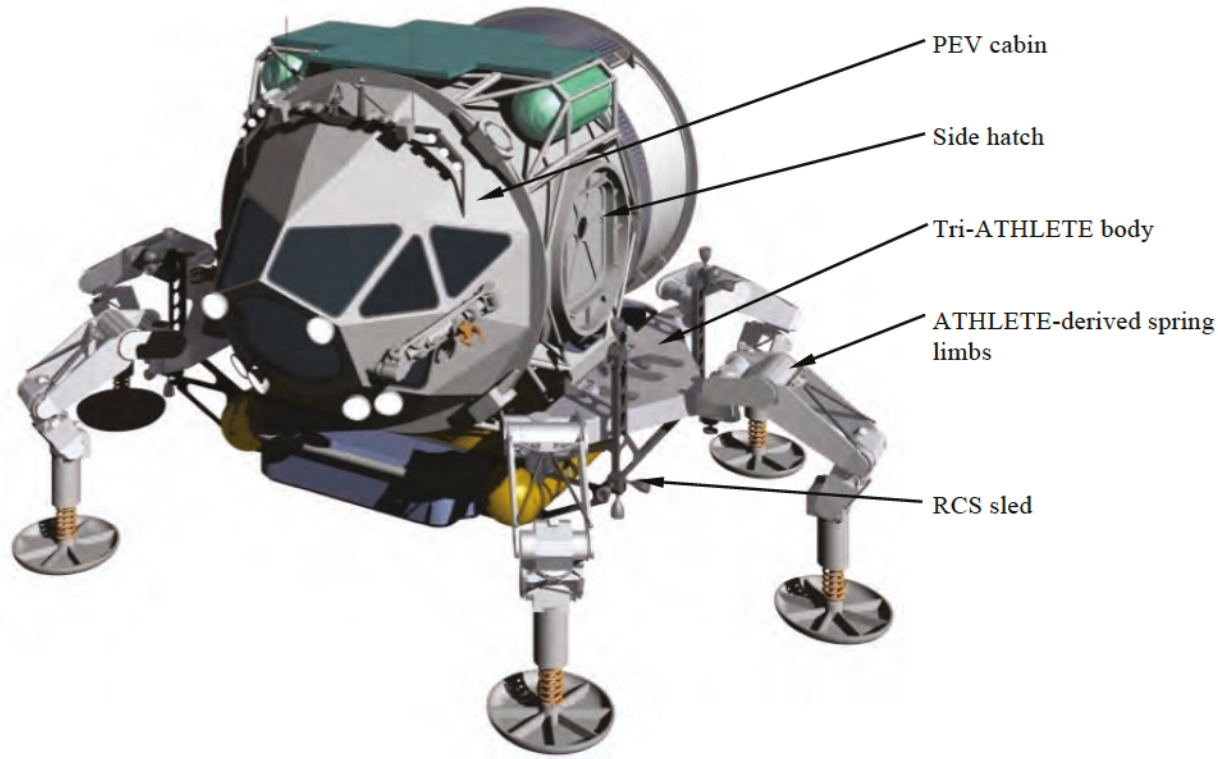



**Figure 7: Phobos hopper with demountable Tri-ATHLETE vehicles (note: alternative cabin design from previous studies)**

### D. Hopper Performance

The simulation used for hopper performance analysis is derived from a flight simulation of the PEV for asteroid exploration. The PEV simulation provides a high fidelity 6DOF modeling of the operation of the spacecraft about a small planetary body. The simulation includes navigation, guidance and control systems models as well as some basic power and propellant usage models. A digital elevation map (DEM) of the small body is used to derive the shape model for the polyhedral gravity model; it also provides a basis for surface contact modeling and for small body scene visualization. The simulation supports real-time execution and provides interactive user displays and controls for human-in-the-loop operation.

The core of the PEV simulation is developed using the Trick Simulation Development Environment and the JSC Engineering Orbital Dynamics (JEOD) modeling package (Lin & Penn 2015). Trick is a simulation development system developed at NASA's Johnson Space Center and is widely used for developing detailed time-based dynamic space systems simulations. Trick supports detailed non-real-time simulation, Monte Carlo simulation and real-time human-in-the-loop simulation. JEOD provides the core astrodynamics environmental and 6DOF spacecraft dynamics modeling. Additional PEV specific models are provided by the NASA Exploration Systems Simulation (NExSyS) team; these include control system models, contact models, thruster models, and human interface models.

Following its successful use for the NASA Research And Technology Studies (RATS) studies in 2012 (Abercromby, Chappell, Litaker, Reagan & Gernhardt 2013), the NExSyS team adapted the PEV simulation to support orbital and surface exploration of Mars' moons Phobos and Deimos. This required enhancements to the overall surface modeling and specifically the surface contact modeling. The navigation, guidance and control models were also modified for the specific needs of operating in the Martian orbital environment.

Further PEV simulation adaptation were made to support the specialized requirements for this small body hopper mobility study. The principal modifications involve the simplified modeling of the mobility aspects of the hopper legs. For the purposes of this study, the simulation does not model the mechanical details of the hopper legs; the simulation only models the ability of the hopper legs to generate a separation velocity from the surface. One significant addition to the simulation was to include a control moment gyro (CMG) model for attitude control during hops. The specialized aspects of surface hopping for mobility and the CMG for attitude control also required additional modifications to the navigation, guidance and control models.

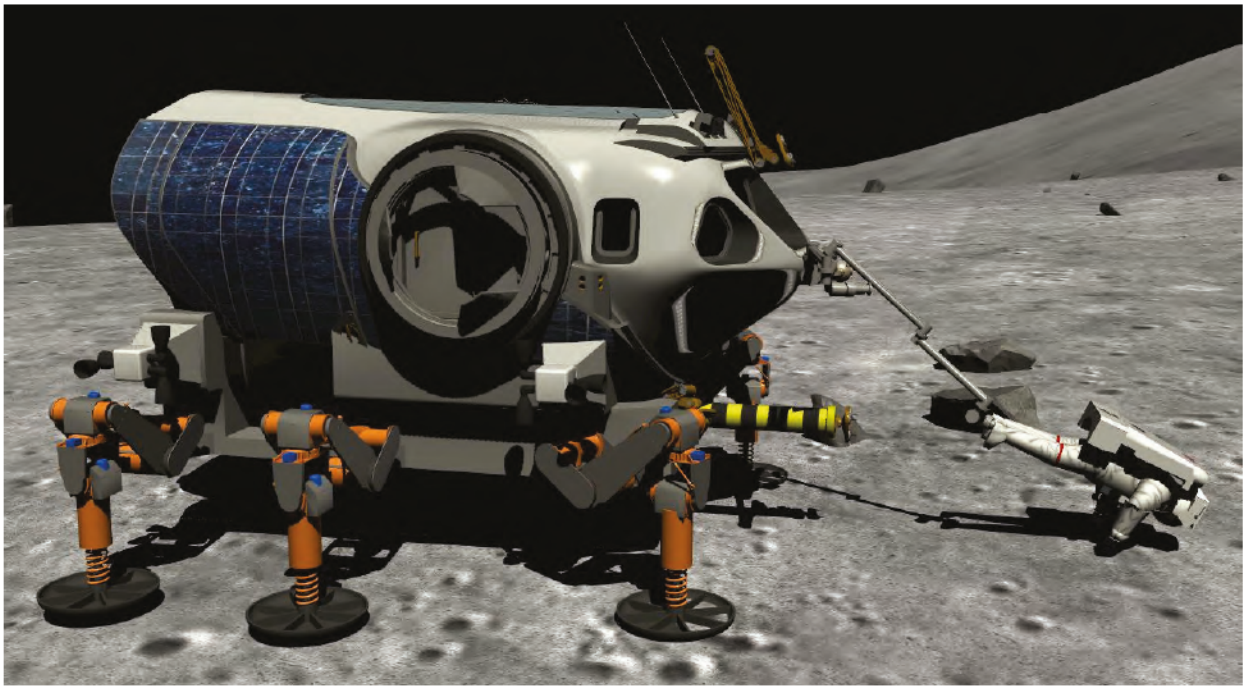


**Figure 8: NExSyS simulation of ATHLETE-based hopper mobility system**

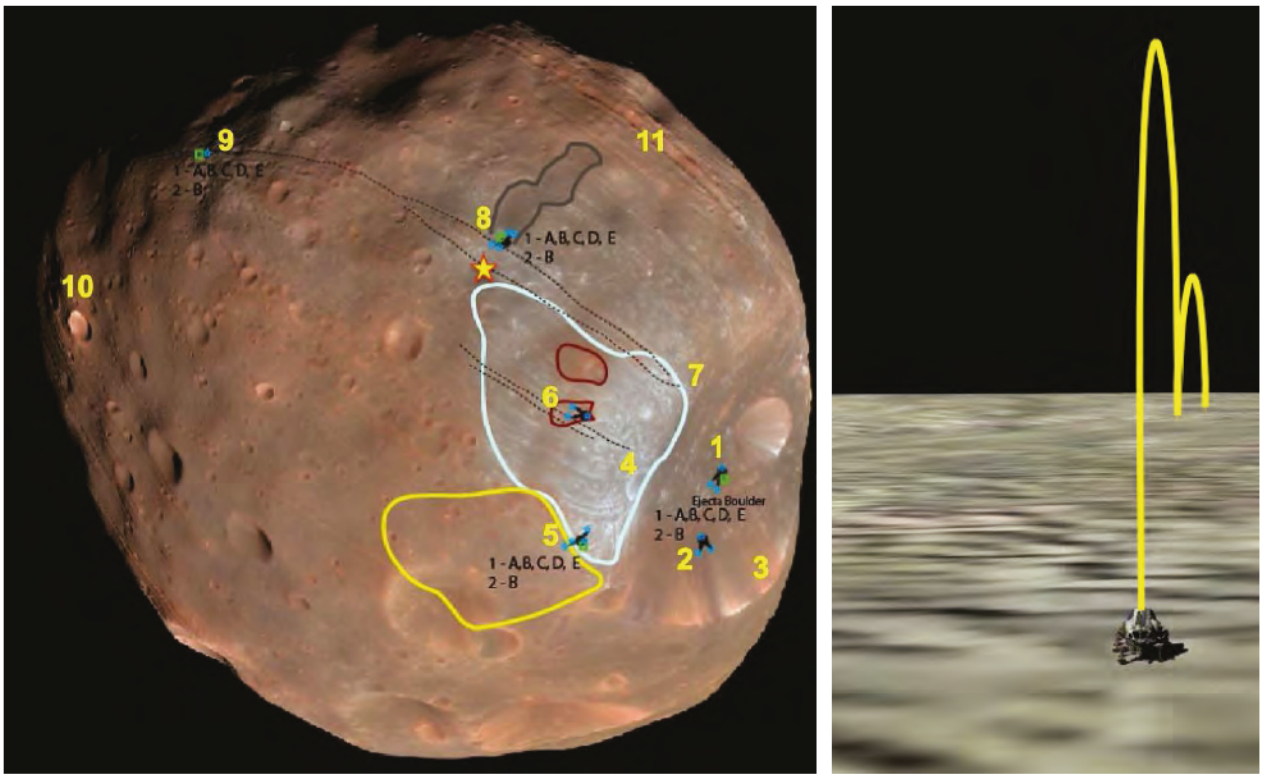



**Figure 9: Multiple hops in succession (right) would be needed to reach sites of interest on Phobos (left)**

The resulting simulation (Figure 8) models three principal modes of transport about Phobos: propulsive only, hopping only and a hybrid of hopping and propulsive. In propulsive mode, the PEV uses its reaction control system (RCS) thrusters for all translational and rotational control. In hopping mode, the PEV uses the hopper legs to generate a separation velocity with respect to the surface and absorb the landing velocity; the CMG provides attitude

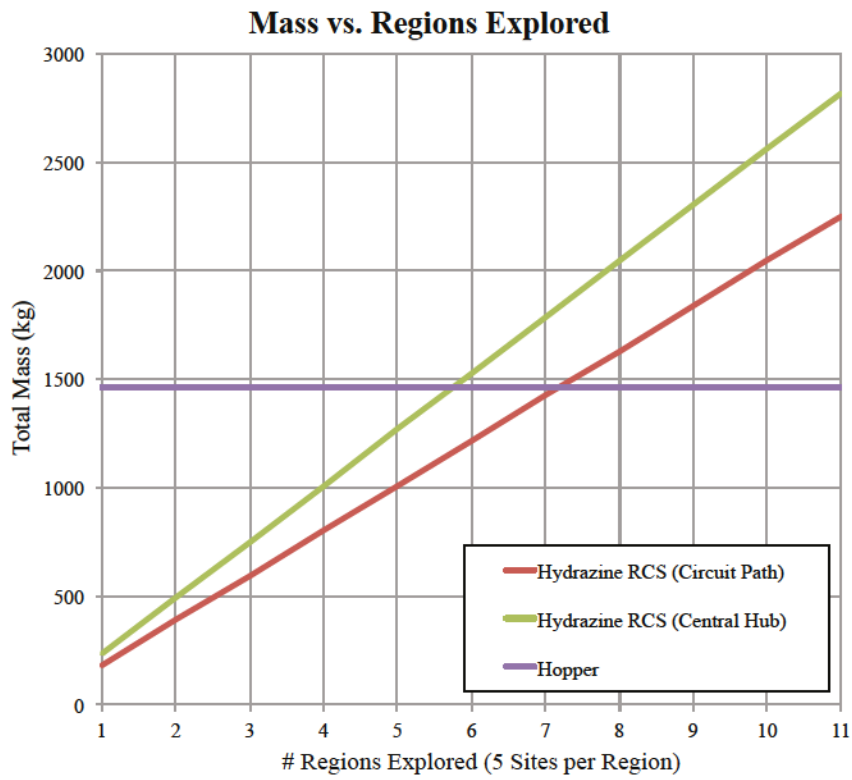
control in flight. Note that the CMG is desaturated with either the RCS thrusters in flight or through ground contact forces on the surface. For the hybrid mode, the PEV hopper legs provide vertical separation from the surface while the RCS thrusters provide horizontal translation and attitude control.

The principal objective of the simulation is collection of data on the consumable resources used during a determined sequence of Phobos exploration traverses (Figure 9). This data is used to assess design trades between RCS propulsion based mobility versus electrically actuated hopping based mobility. A common set of representative traverses were performed using the propulsive mode and the hopping mode. The results were analyzed to assess the design trades between propulsive traverse versus hopping traverse.

Mass is an important metric of interest in the study since mass is a principal driver in the costs associated with delivering a system to the vicinity of Phobos. While the PEV has an RCS system for space based maneuvering which is included the the base PEV mass, additional propellant is required for every additional exploration traverse on Phobos. A non-propellant based method of transportation could potentially reduce or eliminate the need for the additional propellant. The hopper and CMG based system provides an all electric approach. Since electricity can be generated on Phobos with solar arrays, the only additional mass is the hopper and CMG systems.

The hopper mass is based on the designs and analysis in this study. The Hydrazine propellant mass is based on an established PEV vehicle and RCS design (Abercromby, Chappell, Gernhardt, Lee, Howe 2015). Note that the additional mass of the hopper system is independent of the number of regions explored. It represents a one-time constant mass penalty. In comparison, the propellant based RCS system has a per region mass penalty. Note that the RCS propellant mass penalty is also dependent on how you explore the regions. This study looked at two different approaches for traversing Phobos: circuit path and central hub. In the circuit path approach to exploring Phobos, the PEV proceeds from one region to the next without returning to a central habitat between regions. In the central hub approach to exploring Phobos, the PEV returns to the central habitat before exploring the next region.

**Table 9: Hopper mobility versus Hydrazine propellant efficiency**




The focus of this analysis is to determine at what number of traverses the additional mass of propellant exceeds the fixed additional mass of the hopper systems. These results are distilled and presented in the chart showing transport system mass versus number of regions explored (Table 9). The RCS based approaches become more "expensive" in propellant economy when the additional Hydrazine propellant mass exceed the hopper system fixed mass. While these crossover points differ between the "circuit path" and the "central hub" approaches, they both

eventually exceed the hopper system. The data indicates that a hopper system has better mass efficiency when exploring 8 or more regions in a mission.

There are additional benefits of hopping versus RCS traverses. The RCS systems uses thrusters that function by expelling propellant at high velocities in plumes of hot gasses. These plumes are detrimental in at least two ways. First, the plumes will disturb the surface material and potentially raise clouds of visibility obscuring dust in the exploration area. Second, the plumes contain hot corrosive toxic gasses that may contaminate your exploration site. While the hopper system may disturb the surface material on landing, the effects will be limited to just the landing pad locations and is less likely to contaminate the surrounding exploration site.

There are some important caveats to this analysis. Hydrazine was used as the propellant in this analysis since it is space storable, hypergolic, has a reasonable ISP and NASA has a great deal of experience with Hydrazine. While other choices of propellant will change the slopes on the RCS propellant lines, sensitivity analysis based on ISP indicate that modest changes in ISP will not significantly change the results. The efficiency of the hopper system is strongly affected by the properties of the surface material. However, the principal affect of this is in power usage and not weight. So, it might take more or less time to explore the surface depending on the properties of the surface material but would not impact mass. The final caveat has to do with the controllability of the hopper system. While there is a reasonably good understanding of the abilities of the hopper system to generate separation velocities from the surface, there is less certainty in the ability of the hopper system to direct that separation velocity. Even in these cases, the hopper system could be used to generate near vertical separation velocities and use the RCS for translational traverse once the PEV nears maximum altitude. This is the hybrid approach that would still provide propellant mass saving and is an area of continued analysis.

## V. Conclusions

For small bodies, such as Mars' moon Phobos, a small number of target exploration sites (up to six or seven) could use propellant-based systems that are lighter and possibly more efficient than a hopper mobility system. However, propellant-based systems have a limited supply of fuel that would need to be refilled to continue beyond that number. A hopper mobility system that requires renewable electrical power has a fixed system mass, resulting in greater efficiency at larger numbers of exploration sites. Sites of interest may be planned well in advance of a human mission to a small body such as Phobos, but having a renewable electrical powered hopper mobility system would allow for unplanned and continuous use and repurposing of the mobility system beyond the tasks for which it was originally planned.

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## References

AFJ Abercromby; SP Chappell; ML Gernhardt (Oct 2013). Desert RATS 2011: Human and robotic exploration of near-Earth asteroids. *Acta Astronautica*, volume 91, pp34-48.

AFJ Abercromby; SP Chappell; ML Gernhardt; DE Lee; AS Howe (2015). Human Exploration of Phobos. *2015 IEEE Aerospace Conference*, Big Sky, Montana, USA, 7-14 Mar 2015. New York, New York, USA: Institute of Electrical and Electronics Engineers.

AFJ Abercromby; SP Chappell; HL Litaker; ML Reagan; M Gernhardt (2013). NASA Research and Technology Studies (RATS) 2012: Virtual Simulation and Evaluation of Human and Robotic Systems for Exploration of Near-Earth Asteroids. *43rd International Conference on Environmental Systems (ICES2013),* Vail, Colorado, USA, 14-18 July 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

AFJ Abercromby; ML Gernhardt; J Conkin (2013). Fifteen-minute Extravehicular Activity Prebreathe Protocol Using NASA's Exploration Atmosphere (8.2 psia / 34% O2). *43rd International Conference on Environmental Systems (ICES2013),* Vail, Colorado, USA, 14-18 July 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

AFJ Abercromby; ML Gernhardt; J Jadwick (2012). Evaluation of dual multi-mission space exploration vehicle operations during simulated planetary surface exploration. *Acta Astronautica*, vol 90, pp203-214.

AFJ Abercromby; ML Gernhardt; HL Litaker (2010). *Desert Research and Technology Studies (DRATS) 2008 evaluation of Small Pressurized Rover and unpressurized Rover prototype vehicles in a Lunar analog environment.* Washington, DC, USA:. National Aeronautics and Space Administration.

AFJ Abercromby; ML Gernhardt; H Litaker (2012). *Desert Research and Technology Studies (DRATS) 2009: A 14-Day Evaluation of the Space Exploration Vehicle Prototype in a Lunar Analog Environment.* Washington, DC, USA:. National Aeronautics and Space Administration.

SP Chappell; AFJ Abercromby; ML Gernhardt (Aug 2013). NEEMO 15: Evaluation of human exploration systems for near-Earth asteroids. *Acta Astronautica*, volume 89, pp166-178.

SP Chappell; AFJ Abercromby; M Reagan; M Gernhardt (2013). NEEMO 16: Evaluation of Systems for Human Exploration of Near-Earth Asteroids. *43rd International Conference on Environmental Systems (ICES2013),* Vail, Colorado, USA, 14-18 July 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

J Crusan (2014). An Evolvable Mars Campaign. *NASA Exploration Forum*. NASA Headquarters, Washington, DC, 2014.

ML Gernhardt; AFJ Abercromby (2008). Health and Safety Benefits of Small Pressurized Suitport Rovers as EVA Surface Support Vehicles. *AsMA 2008 Annual Scientific Meeting*. Boston, MA, USA: Aerospace Medical Association.

B Griffin; R Lepsch; J Martin; R Howard; M Rucker; E Zapata; C McCleskey; AS Howe; N Mary; P Nerren (2015). Small Habitat Commonality Reduces Human Mars Mission Costs. *AIAA Space 2015 Conference & Exhibition*, Pasadena, California, USA, 31 Aug – 2 Sep 2015. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

M Heverly; J Matthews; M Frost; C McQuin (2010). Development of the Tri-ATHLETE Lunar Vehicle Prototype. *40th Aerospace Mechanisms Symposium*. NASA Kennedy Space Center, Cocoa Beach, Florida, USA, 12 – 14 May 2010.

AS Howe (2015). A Modular Habitation System for Human Planetary and Space Exploration. *45th International Conference on Environmental Systems (ICES2015)*, Belleview, Washington, USA, 12-16 July 2015. Lubbock, Texas, USA: Texas Tech University.

AS Howe; M Simon; D Smitherman; R Howard; L Toups; S Hoffman (2015). NASA Evolvable Mars Campaign: Mars Surface Habitability Options. *2015 IEEE Aerospace Conference*, Big Sky, Montana, USA, 7-14 Mar 2015. New York, New York, USA: Institute of Electrical and Electronics Engineers.

AS Howe; B Wilcox; C Mcquin; D Mittman; J Townsend; R Polit-Casillas; T Litwin (2014). Modular Additive Construction Using Native Materials. *Proceedings of the Fourteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2014)*. St Louis, Missouri, 27-29 Oct 2014. Reston, Virginia, USA: American Society of Civil Engineers.

AS Howe; B Wilcox; C McQuin; J Townsend; R Rieber; M Barmatz; J Leichty (2013). Faxing Structures to the Moon: Freeform Additive Construction System (FACS) (AIAA2013-5437). *AIAA Space 2013 Conference & Exhibition*. San Diego, California, USA, 10-12 Sep 2013. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

A Lin; J Penn (2015). *The Trick Simulation Development Environment*. Retrieved 7 July 2015 from: https://github.com/nasa/Trick/wiki/Users-Guide

H Litaker; M Chen; R Howard; B Cloyd (nd). *Human Factors Assessment for the Space Exploration Vehicle (SEV) GEN 2A Habitable Volume Three Day Study-Research and Technology Studies (RATS) Phase 2*. Washington, DC, USA:. National Aeronautics and Space Administration. In Review.

RO Shelton (2014). *JSC Engineering Orbital Dynamics: (JEOD)* Top Level Document, Document Revision 1.3. JSC-61777-docs, December 2014.

J Townsend; D Mittman (2012). Driving ATHLETE: Analysis of Operational Efficiency (AIAA2012-5116). *AIAA Space 2012 Conference & Exhibition*. Pasadena, California, USA, 11 – 13 Sep 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

MS Wallace; JS Parker; NJ Strange; D Grebow (2012). Orbital operations for Phobos and Deimos exploration (AIAA2012-5067). *AIAA/AAS Astrodynamics Specialist Conference*, 13-16 Aug 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

BH Wilcox (2012). ATHLETE: A Limbed Vehicle for Solar System Exploration. *IEEE Aerospace Conference*, 3 - 10 Mar 2012, Big Sky, Montana, USA. New York, NY, USA: Institute of Electrical and Electronics Engineers.

BH Wilcox; T Litwin; J Biesiadecki; J Matthews; M Heverly; J Townsend; N Ahmad; A Sirota; B Cooper (2007). ATHLETE: A Cargo Handling and Manipulation Robot for the Moon. *Journal of Field Robotics*, Vol 24, No 5, pp 421-434.