Outpost Assembly using the ATHLETE Mobility System

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Abstract -- **A planetary surface outpost will likely consist of elements delivered on multiple manifests, that will need to be assembled from a scattering of landings. Using the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) limbed robotic mobility system, the outpost site can be prepared in advance through leveling, paving, and in-situ structures. ATHLETE will be able to carry pressurized and non-pressurized payloads overland from the lander descent stage to the outpost location, and perform precision docking and assembly of components. In addition, spent descent stages can be carried to assembly locations to form elevated decks for external work platforms above the planet surface. This paper discusses several concepts that have been studied for possible inclusion in the NASA Evolvable Mars Campaign human exploration mission scenarios.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. THE ATHLETE MOBILITY SYSTEM.....1
3. SITE PREPARATION.....3
4. LANDER OFFLOAD AND MOBILITY.....4
5. OUTPOST BUILD-UP 6
6. FUTURE WORK.....8
ACKNOWLEDGMENTS 8
REFERENCES.....8
BIOGRAPHY 9

1. INTRODUCTION

Deep space and planetary surface missions will send human crews tremendous distances away from Earth and the possibility of resupply. A human mission to Mars will require multiple launches and landings of pressurized habitat modules, mobilty & power systems, logistics, and equipment enough to construct an outpost for long duration stays [1, 2]. Mission architectures trade monolithic volumes versus smaller assembled modular cabins for lunar missions in the Constellation Architecture Team Lunar Surface Systems architecture [3, 4, 5, 6, 7] and the Evolvable Mars Campaign [8, 9, 10, 11]. Multiple landers (Figure 1) in Entry, Descent, and Landing (EDL) cannot pinpoint land in the same location due to the possibility of ejecta from the exhaust kicking up material that might damage equipment already on the surface. For a Mars outpost, descent stages may need to be placed no closer than one kilometer apart and will need mobility systems to offload materials and collect them to a central locatioin.

Figure 1: Habitat module on lander deck (with deployable ramp off-load aid)

This paper describes recent concepts that have been studied for site preparation, descent stage offload, mobility, and outpost construction on Mars for NASA's Evolvable Mars Campaign.

2. THE ATHLETE MOBILITY SYSTEM

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system (Figure 2) is a six-limbed wheel-on-limb robotic mobility platform that is capable of transporting large cargo efficiently on both rolling and rough terrain [12, 13].

Figure 2: ATHLETE mobility system

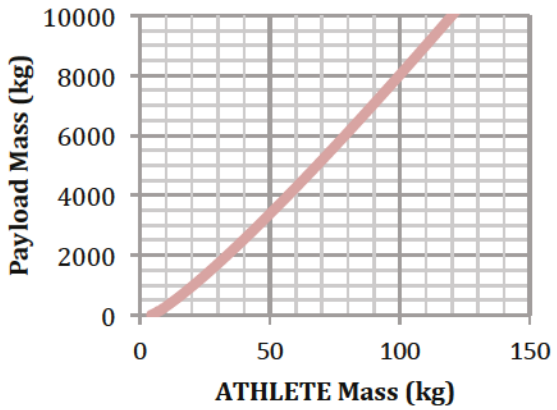

Figure 3: Estimated payload vs ATHLETE mass in Phobos gravity

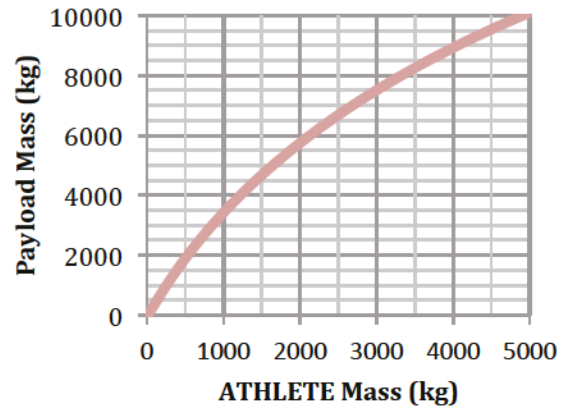

Figure 4: Estimated payload vs ATHLETE mass in Mars gravity

Table 1: Stepped mass values for ATHLETE in Phobos gravity, including power for rolling and hexapod gait mobility

Payload	ATHLETE	Total	%	Rolling	Hexapod
100 kg	6.7 kg	107 kg	0.06	1 W	12 W
200	8.5	209	0.04	2	24
300	10.2	310	0.03	3	35
400	11.8	412	0.03	4	47
500	13.4	513	0.03	4	59
600	14.9	615	0.02	5	70
700	16.4	716	0.02	6	82
800	17.8	818	0.02	7	93
900	19.2	919	0.02	8	105
1,000	20.6	1,021	0.02	9	116
2,000	33.6	2,034	0.02	17	232
3,000	45.6	3,046	0.01	26	347
4,000	57.1	4,057	0.01	35	463
5,000	68.1	5,068	0.01	43	578
6,000	78.9	6,079	0.01	52	693
7,000	89.4	7,089	0.01	61	808
8,000	99.8	8,100	0.01	69	923
9,000	110.0	9,110	0.01	78	1,039
10,000	120.0	10,120	0.01	87	1,154
20,000	215.2	20,215	0.01	173	2,305
30,000	305.1	30,305	0.01	259	3,455
40,000	391.9	40,392	0.01	345	4,605
50,000	476.7	50,477	0.01	432	5,754
60,000	560.0	60,560	0.01	518	6,904
70,000	642.3	70,642	0.01	604	8,053
80,000	723.7	80,724	0.01	690	9,203
90,000	804.5	90,805	0.01	776	10,352
100,000	884.7	100,885	0.01	863	11,501

Table 2: Stepped mass values for ATHLETE in Mars gravity using rolling mobility

Payload	ATHLETE	Total	%	Power
100 kg	35.0 kg	135 kg	0.26	149 W
200	60.0	260	0.23	287
300	84.4	384	0.22	424
400	108.7	509	0.21	561
500	132.9	633	0.21	698
600	157.3	757	0.21	836
700	182.0	882	0.21	973
800	206.8	1,007	0.21	1,111
900	232.0	1,132	0.20	1,249
1,000	257.5	1,258	0.20	1,388
2,000	533.4	2,533	0.21	2,796
3,000	852.5	3,853	0.22	4,252
4,000	1,220.9	5,221	0.23	5,762
5,000	1,644.6	6,645	0.25	7,333
6,000	2,130.6	8,131	0.26	8,973
7,000	2,687.5	9,688	0.28	10,691
8,000	3,326.2	11,326	0.29	12,500
9,000	4,060.4	13,060	0.31	14,414
10,000	4,908.5	14,909	0.33	16,453
11,000	5,896.0	16,896	0.35	18,647
12,000	7,058.7	19,059	0.37	21,034
13,000	8,452.8	21,453	0.39	23,676
14,000	10,172.0	24,172	0.42	26,677
15,000	12,398.0	27,398	0.45	30,237
16,000	15,600.0	31,600	0.49	34,875

The fundamental premise of the ATHLETE system is that for sufficiently large systems, by designing the wheels and wheel actuators for relatively benign terrain, the system saves enough mass to offset the mass of the robotic limbs. At the heart of the ATHLETE concept is the limb, which is repeated six times around the body of the robot [14]. 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.

In Phobos gravity sizing of an ATHLETE for specified payload mass is shown in Figure 3, with discrete stepped values shown in Table 1. Similarly, for a Mars surface mobility system ATHLETE versus payload mass is shown in Figure 4, with stepped mass values described in Table 2.

As of this writing, the Evolvable Mars Campaign is considering five and ten metric ton capacity mobility systems. Therefore, in Table 2 a five ton (5,000kg) capacity ATHLETE would have a mass of 1,645kg, and a ten ton payoad capacity ATHLETE would have a mass of 4,909kg. One trade might show that a pair of 1,645kg ATHLETEs could share a 10 ton load, and be lighter than a single 4,909kg system. These trades are currently in progress.

3. Site Preparation

A key feature of the ATHLETE design is that each of the limbs can serve as general-purpose robotic manipulators. 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. A variety of tools have been developed for ATHLETE, such as dozer blades (Figure 5), backhoe shovels (Figure 6), drills (Figure 7), and other tools.

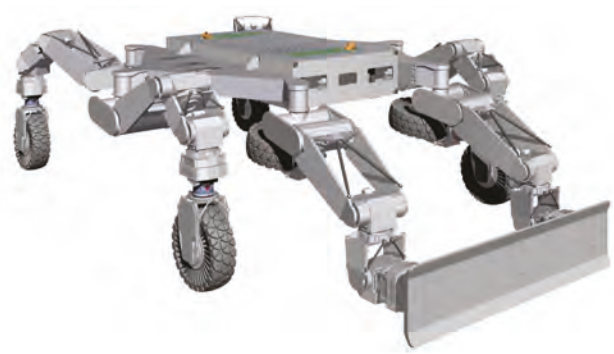

Figure 5: ATHLETE fitted with dozer blade

Figure 6: ATHLETE fitted with backhoe shovel

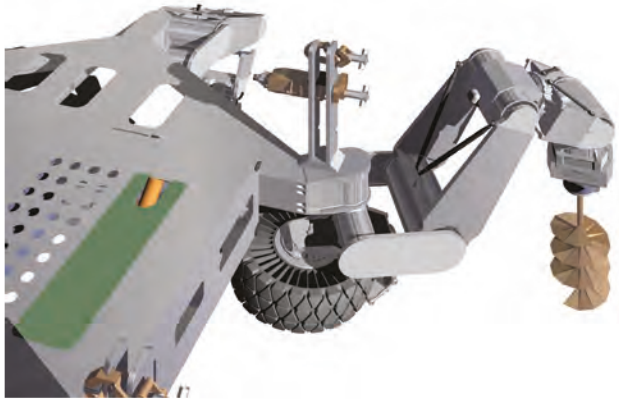

Figure 7: ATHLETE using a variety of implements, including auger drill for excavation

Used in conjnction with the NASA Kennedy Space Center SwampWorks Regolith Advanced Surface Systems Operations Robot (RASSOR) and other excavators [15], ATHLETE can be placed in advance for site smoothing and preparation. Fitted with an additive construction print head such as University of Southern California's Contour Crafting [16], or other Freeform Additive Construction System (FACS) technologies [17, 18], ATHLETE can also be used to pave landing pads or as a large scale 3D printer of walls, berms, and other structures (Figure 8).

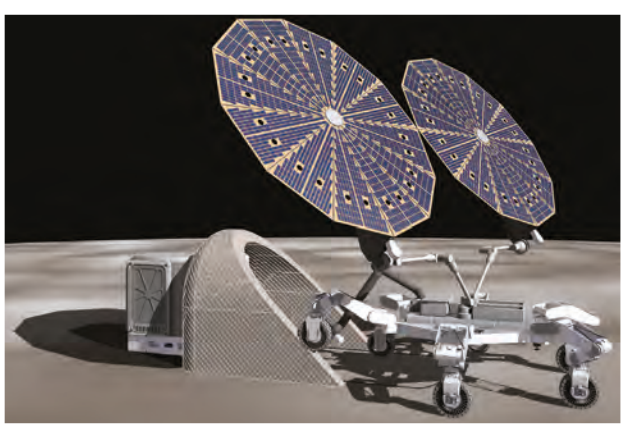

Figure 8: ATHLETE as a Freeform Additive Construction System (FACS) [17, 18]

4. Lander Offload and Mobility

Whereas small payloads such as the Mars Science Laboratory (MSL) aka "Curiosity" could use bottom-slung "sky crane" descent stage designs, very large cargos as of this writing need flat-topped landers for delivery to the surface.

Figure 9: Lunar Surface Systems lander offload scenario [5]

For the Constellation Architecture Team Lunar Surface Systems it was proposed to use ATHLETE to partially climb up onto the lander deck and grasp the payload from both sides to slide it off sideways (Figure 9). Scaled hardware was tested in the field during Desert Research and Technology Studies (D-RATS) analog field tests (Figure 10).

Figure 10: D-RATS field tests off-loading [13]

For the Evolvable Mars Campaign several concepts have been studied, including ATHLETE and the NASA Langley Lunar Surface Manipulation System (LSMS) crane, also applicable to the Mars surface. ATHLETE could be used in the same way as was demonstrated at D-RATS for offloading multiple modules from the lander deck (Figure 11). ATHLETE could also be used in conjunction with a deployable ramp (Figure 12).

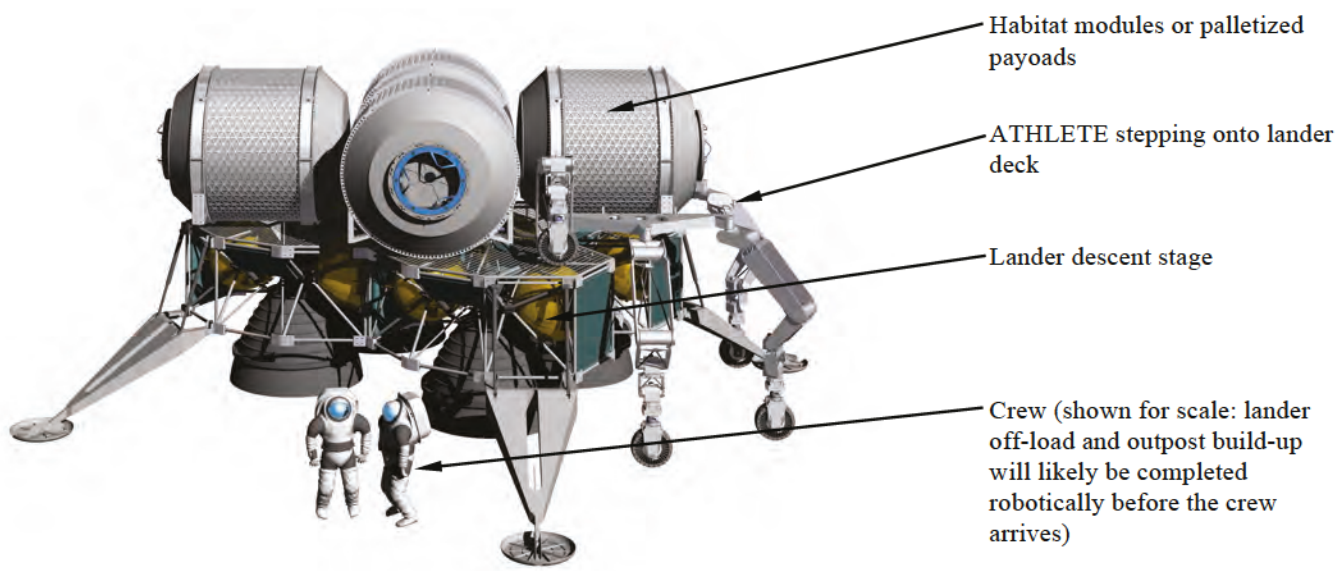

Figure 11: Mars off-load scenario: using ATHLETE to remove elements from the deck

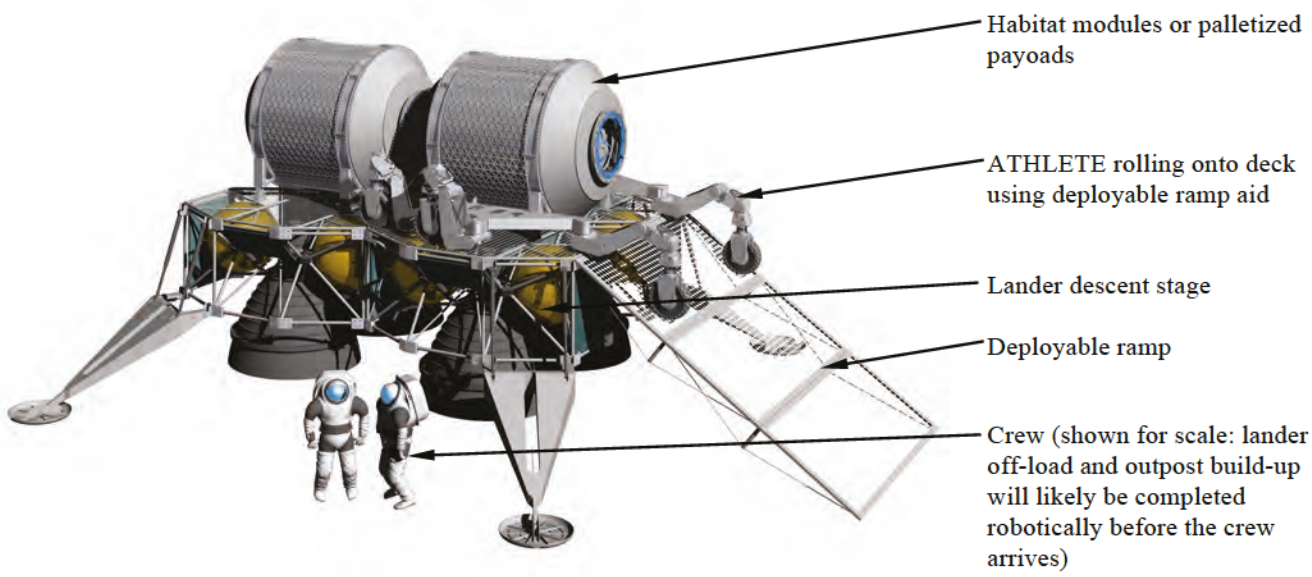

Figure 12: Mars off-load scenario: using a deployable ramp for removing elements

ATHLETE can also be used to carry an LSMS crane, where the limbs can be outstretched to function as outriggers (Figure 13).

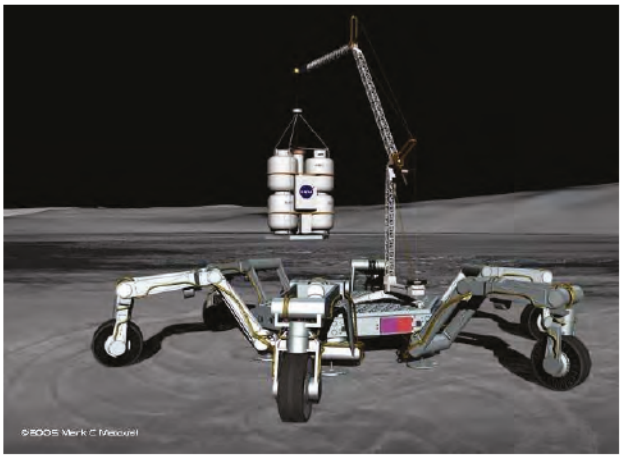

Figure 13: Using ATHLETE as an outrigger for the Lunar Surface Manipulator System (LSMS) crane (by Mark C Maxwell [19])

Once a habitat module or palletized cargo has been offloaded, ATHLETE can either set it onto the surface (Figure 14), place it onto a mobility chassis (Figure 15), or carry it overland to a new location, such as the outpost congregation point. ATHLETEs (singly or in multiples depending on the mass of the descent stage and capacity of the ATHLETE) can carry empty landers from their original landing spots to alternate locations for reuse. Figure 16 shows an ATHLETE carrying a lander that has re-stowed its legs.

Figure 14: ATHLETE can set payloads directly on the surface

Figure 15: ATHLETE can set elements onto mobility chassis

Figure 16: ATHLETE carrying a lander to a desired location

5. Outpost Build-up

The conventional approach to outpost build-up has been described as sequentially docking mulitple pressurized habitat modules together as they arrive via descent stage [3, 4, 5, 6, 7, 9, 10, 11]. This method of automated construction has been demonstrated using ATHLETE during D-RATs analog tests in Moses Lake, Washington with docked modules (Figure 18), and Black Point Lava Flow, Arizona showing placement and separation of Tri-ATHLETE vehicles (Figure 17).

A scenario for automated outpost build-up using the conventional approach would proceed as follows:

1. Mobility, construction equipment, and power systems are delivered
2. Outpost site is smoothed and prepared, power systems placed
3. First habitat module is delivered, and carried to its target location at the prepared site
4. Subsequent landers deliver additional modules, which are sequentially docked to the first module to expand the pressurized volume

The conventional outpost build-up is usually assumed to be on a dusty site. Some alternatives allow for in-situ paving to reduce the disturbance of dust. If regolith excavation and manipulation capable equipment is available, prefabricated panels made from regolith can be constructed into an unpressurized garage, with loose regolith piled on top for radiation shielding (Figure 19).

Another option for outpost build-up conducted during this study is to construct a raised dust-reducing platform out of spent descent stages. In this scenario the first lander would stay in place with its habitat load (Figure 20), and subsequent landers would be offloaded and carried next to the first one (Figure 21) to establish a raised platform (Figure 22).

Figure 17: ATHLETE placing elements on the surface by sideways separation (top), field-tested at D-RATS (bottom)

Figure 18: Using ATHLETEs to dock multiple habitat modules together in outpost build-up

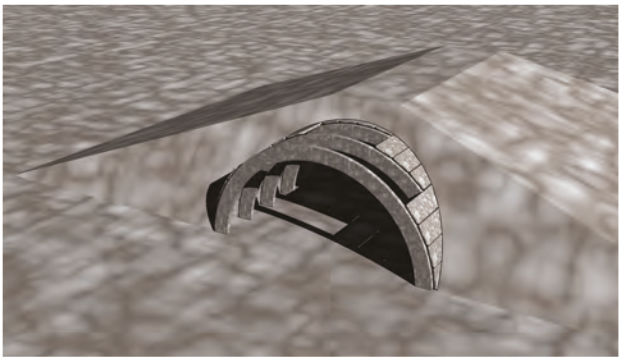

Figure 19: Unpressurized ISRU radiation garage

Figure 20: First lander with habitat is not transportable due to mass limitations

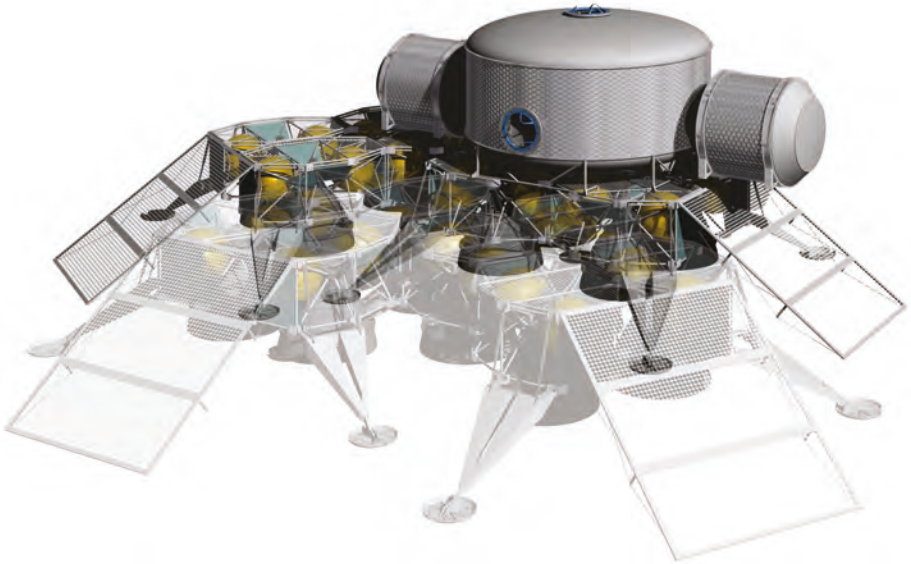

Figure 21: Subsequent landers are off-loaded and carried to first lander location

Figure 22: Raised, dust-reducing platform consisting of multiple landers in close proximity

6. Conclusions

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system is not just a heavy cargo carrier, but has multiple uses, including excavation, site preparation, lander off-load, cargo handling, tool manipulation, outpost constructor, paver, driller, and other uses. These various uses have been demonstrated in the field using prototype hardware. As human Mars missions are planned and executed, many of the challenges of planetary outpost construction can be enabled by these demonstrated capabilities.

Acknowledgments

The research described in this paper was carried out at the National Aeronautics and Space Administration (NASA), and the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. Copyright 2016. All rights reserved.

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Biography

A. Scott Howe *is a licensed architect and robotics engineer at NASA's Jet Propulsion Laboratory. He earned PhDs in industrial and manufacturing systems engineering from Hong Kong University and in architecture from University of Michigan. Dr. Howe spent 13 years of practice in Tokyo, Japan, and taught for 6 years at Hong Kong University. He specializes in robotic construction and currently is on the NASA development team building long-duration human habitats for deep space and permanent outposts for the moon and Mars. Dr. Howe is also a member of the JPL All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system development team, Asteroid Redirect Mission (ARM) capture mechanism team, and Mars Sample Return (MSR) Orbiter design team.*

Brian H Wilcox *is a JPL Fellow and the manager of Space Robotics Technology in the Solar System Exploration Directorate and is the Principal Investigator for ATHLETE – the All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer (see http://www-robotics.jpl.nasa.gov/tasks/index.cfm). He was the supervisor of the JPL Robotic Vehicles Group for over 20 years, during which the group was responsible for planetary rover development leading up to the Sojourner and Mars Exploration Rovers. The group was responsible for development of the electronics, control, flight software, ground software, and mission operations of the Sojourner rover that explored part of Mars in 1997. Brian was personally responsible for the imaging and hazard detection sensors and the hazard avoidance algorithms on Sojourner. He has a B.S. in Physics and a B.A. in Mathematics from the University of California at Santa Barbara, and an M.S. in Electrical Engineering from the University of Southern California.*