ATHLETE: A Cargo and Habitat Transporter for the Moon

Brian H. Wilcox
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr. M/S 303-300
818-354-4625
brian.h.wilcox@jpl.nasa.gov

Abstract—As part of the NASA Exploration Technology Development Program, the Jet Propulsion Laboratory is developing a vehicle called ATHLETE: the All-Terrain Hex-Limbed Extra-Terrestrial Explorer. [1] [2] The vehicle concept is based on six wheels at the ends of six multi-degree-of-freedom limbs. Because each limb has enough degrees of freedom for use as a general-purpose leg, the wheels can be locked and used as feet to walk out of excessively soft or other extreme terrain. Since the vehicle has this alternative mode of traversing through (or at least out of) extreme terrain, the wheels and wheel actuators can be sized only for nominal terrain. There are substantial mass savings in the wheels and wheel actuators associated with designing for nominal instead of extreme terrain. These mass savings are comparable-to or larger-than the extra mass associated with the articulated limbs. As a result, the entire mobility system, including wheels and limbs, can be about 25% lighter than a conventional mobility chassis for planetary exploration. A side benefit of this approach is that each limb has sufficient degrees-of-freedom for use as a general-purpose manipulator (hence the name "limb" instead of "leg"). Our prototype ATHLETE vehicles have quick-disconnect tool adapters on the limbs that allow tools to be drawn out of a "tool belt" and maneuvered by the limb. A rotating power-take-off from the wheel actuates the tools, so that they can take advantage of the 1+ horsepower motor in each wheel to enable drilling, gripping or other power-tool functions.

Architectural studies have indicated that a useful role for ATHLETE in lunar exploration is to "walk" cargo off the payload deck of a lunar lander and transport it across the lunar surface. Current architectural approaches are mostly focused on the concept that the lunar lander descent stage will use liquid hydrogen as a propellant. This is the highest-performance chemical fuel, but is low density and hence requires large tanks. As a result, the cargo deck of the lander is very high off the ground (over 6 meters in current concepts [1]). An ATHLETE vehicle with limbs this long is able to directly step onto the ground, moving off the lander by stepping with its rear limbs only onto the widely-spaced "hard points" on the top deck of the lander space-frame structure. One major motivation for surface mobility is that any lander will spray ejecta from the plume of the descent engine as it lands. This ejecta can reach speeds of several kilometers per second, and could cause significant damage to any exposed hardware. Thus it is desirable for all surface assets to stay away from any landing zone (out of "ballistic line-of-sight"), and then to move in after landing to offload crew or cargo from the newly-arrived lander.

Some of the most attractive cargo elements to make mobile are habitats. Mobile habitats can enable or facilitate wide-area or global-scale exploration of the moon by acting as local bases in support of smaller crewed rovers. These mobile bases would "stay on the high ground" in polar regions to collect as much solar energy as possible (for their own use, and to recharge the small rovers), to act as a communication relays when the smaller pressurized rovers descend into occluded regions, to provide more spacious living accommodations than offered by the small rover, and to provide "dis-similar redundancy" for crew mobility (to get back to the ascent stage, at a minimum) in the event of failure of the smaller rover.

Work described in this paper includes the outfitting of two ATHLETE sub-scale prototypes with habitat mockups. Field testing included traverses in excess of 1 km and precision docking of the two habitat shells with an accuracy of a few mm.

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1. INTRODUCTION

The All-Terrain, Hex-Limbed, Extra-Terrestrial Explorer (ATHLETE) is a vehicle that is being developed by JPL as part of the Human-Robot Systems (HRS) Project managed by Robert Ambrose of the Johnson Space Center (JSC). HRS is one of several projects funded by the NASA Exploration Technology Development Program (ETDP) that is developing new technology in support of human lunar return. ATHLETE was conceived to transport large masses

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[2] IEEEAC paper #1417, Version 5, Updated Dec 3, 2008

Figure 1a: ATHLETE SDM vehicle climbing a natural escarpment.

Figure 1b: ATHLETE SDM vehicles under test at Dumont Dunes in California.

(cargo and habitats) on the moon [2]. Two subscale prototype "Software Development Model" (SDM) vehicles have been built and tested (Figure 1), each with a mass of about 850 kg and a payload (on Earth) of 300 kg. The SDM vehicles are built with hexagonal frames 2.75 m across, with each of the 6-degree-of-freedom limbs standing a maximum of 2.08 m to the hip pitch joint center. At the end of each limb is a wheel with a diameter of 0.71 m, with each wheel having on one side a "power take-off" square key (equivalent to a ½" socket drive) that rotates with the wheel. A quick-disconnect tool adapter allows a variety of tools to be affixed over the power take-off, and a pair of high-definition stereoscopic cameras fold out when the tool adapter opens to receive a tool, so the operator can use the 6-DOF limb as a general-purpose manipulator.

In 2006, NASA convened the "Lunar Architecture Team" (LAT) led by Tony Lavoie of the Langley Research Center, with team members drawn from NASA headquarters and many of the NASA field centers (including this author). The team studied ways to implement Human Lunar Return (HLR) that is identified as a key objective of the "Vision for Space Exploration" [3]. The original LAT results were presented at the 2nd AIAA Conference on Space Exploration in Houston TX, Dec 4-6, 2006 [4]. LAT recommended that mobile landers be studied in the next phase of the LAT process. That next phase, LAT-2, was led by Andy Thomas of JSC and began work in January 2007, reporting its conclusions at the AIAA Space 2007 Conference in Long Beach, CA, September 18-20, 2007 [5]. This LAT-2 out-brief concludes that

- "extended-range surface mobility is essential",
- the "wheel on leg carrier facilitates unloading and assembly of surface assets",
- the "wheel-on-leg surface carrier offers a ... Winnebago mode of exploration" where "carrier and habitat module ... create [a] fully equipped mobile habitat [that] drives robotically to new site"
- "crew drive with it [the mobile habitat], or to it in a [small pressurized] rover, or land by it for an extended sortie"
- "after crew departure, [the] mobile habitat drives to different site and awaits arrival of next crew."

2. THE ATHLETE CONCEPT

The premise of ATHLETE is that a vehicle that can "walk" out of extreme terrain and use wheels to efficiently roll in nominal terrain will result in a vehicle that will be both more capable and less massive than a conventional all-terrain vehicle. The reason it will be lighter is that the wheels needed to traverse nominal terrain (e.g. 97% of the lunar surface) will be smaller and require less peak torque than wheels for a vehicle that can <u>never</u> be permitted to get stuck. Such vehicles (current Mars rovers are good examples) must be able to successfully traverse perhaps 99.99% of the surface, so that one could expect to be able to travel for many years without getting stuck. In contrast, it might be acceptable for a rolling ATHLETE to get stuck once or twice a day, since it can simply walk out of extreme terrain.

The "Lunar Sourcebook" provides a plot of data from Apollo and Lunokhod regarding the load-bearing properties of the lunar surface [6]. Using this data, we estimate that average lunar terrain has a compressibility of about 3 MPa per meter of depth. We further estimate that the "2-σ softest" terrain has a compressibility of about 1 MPa/m (e.g. roughly the softest published measurement data). Lastly, based on anecdotal evidence from Lunokhod and Apollo (Figure 2), we estimate that the "4-σ softest" terrain has a compressibility of about 0.25 MPa/m, mostly around the rims of the most recent craters.

Based on these results, a wheel that only rolls over "2-σ softest" terrain can have about four times ground pressure as one that must be able to successfully roll over the 4-σ softest terrain. Wheel mass is expected to scale proportionately with load at constant wheel diameter, and proportionately with the cube of the dimension if all elements are scaled together (with a load that increases by the square of the

Figure 2: Apollo boot-prints in ~"4-σ soft terrain" (top) and nominal terrain (bottom) giving anecdotal evidence that terrain >10X softer than the average exists (e.g. 10 cm deep boot-prints vs 1 cm deep in nominal terrain).

dimension). Since the wheel contact patch area increases with the square of the dimension, the reduction in ground pressure enabled by the ATHLETE concept allows the wheels to be about half the diameter and one-fourth the mass of those used for a conventional vehicle of the same mass.

A conventional all-terrain vehicle also needs to have substantial rim thrust available on each wheel to get out of bad situations, such as when one wheel drops into a hole, causing a body shift such that the center-of-mass projects largely onto the wheel down in the hole. A rule-of-thumb used at JPL for such vehicles is that every wheel needs to have a stall rim thrust of at least half of the total vehicle weight in the local gravity field. So the combined rim thrust of a conventional 6-wheeled all-terrain vehicle (e.g. a Mars rover) needs to be 3 times the vehicle weight. For ATHLETE, this design rule does not apply, since ATHLETE can walk out of this bad situation, lifting the wheel out of the hole without any requirement for traction or rim thrust. All that is required is that the wheels provide adequate thrust when climbing a moderate slope in soft terrain. Soil-mechanics models show that the thrust required to move a vehicle up a 20-degree slope in 2-sigma soft terrain is about 60% of the total vehicle weight. Thus the combined rim thrust for the ATHLETE vehicle is one-fifth that needed for a conventional all-terrain vehicle, and because of the smaller wheels the peak torque is only one-tenth as great. The mass of a gearbox is generally proportional to its peak output torque. Also, the electric motor in a conventional planetary rover must be substantially oversized compared to ATHLETE because the stall and cruise speed/torque requirements in a conventional vehicle are poorly matched to a single-speed gearbox. The combined savings in mass associated with the smaller wheels, the lower-torque wheel drive actuators, and the more efficient utilization of the motor saves more mass than the rest of the limb actuators combined, allowing the overall wheel-on-leg carrier to be about 25% lighter than alternative all-terrain mobility systems [7].

Figure 3 shows the use of tools by ATHLETE. Tool use is one of the "free" benefits of the ATHLETE vehicle configuration. Each wheel has a quick-disconnect tool adapter that can be used to extract any sort of tool from a "holster". Each tool adapter locks the tool over a rotating power take-off that uses the wheel drive actuator to power

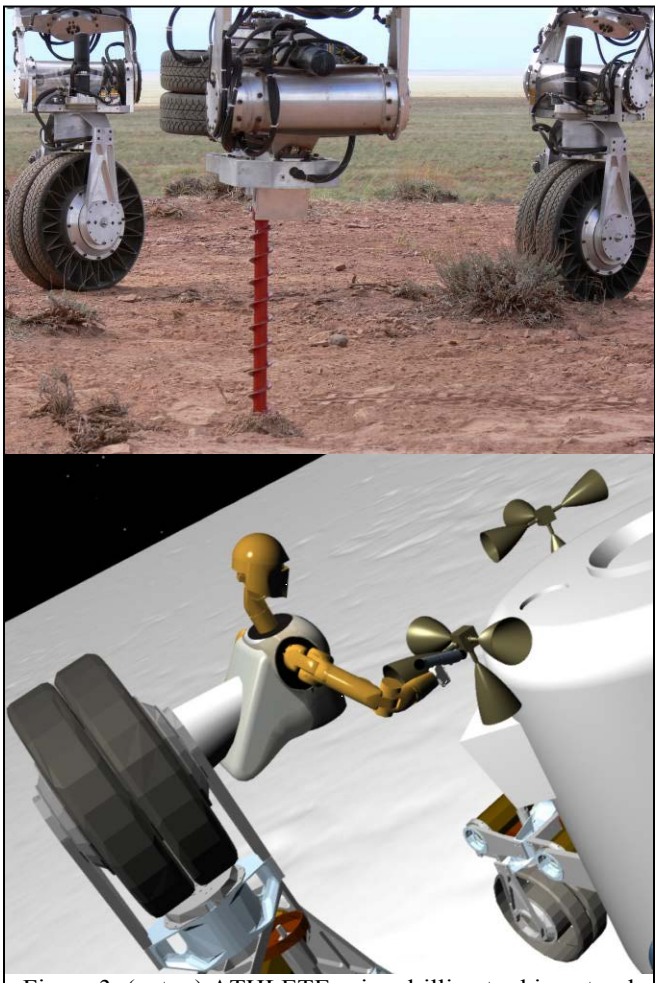

Figure 3: (a, top) ATHLETE using drilling tool in natural terrain, (b, bottom) ATHLETE using Robonaut anthropomorphic robot developed by the Johnson Space Center for tasks requiring human-like dexterity.

the tool. This can be direct mechanical power, as seen in Figure 3a where ATHLETE is drilling into natural terrain, or indirect power, where the rotating key is used to drive a generator to supply electrical power to a more complex tool such as the anthropomorphic robot "Robonaut" developed by the NASA Johnson Space Center. Complex tools such as these would use ATHLETE as a "cherry picker" positioning device, and then be wirelessly controlled from astronauts inside or outside the vehicle, or from ground controllers on Earth. Astronaut control from inside the habitat would include "telepresence" control, where the anthropomorphic robot would have extreme-bandwidth and virtually no round-trip time delay, so that the human operator feels as if they are performing the task directly. In this way, humans can perform complex and delicate tasks outside the habitat. If any limb actuators fail, usually the leg retains some limited capability. In the worst-case failure of the hip pitch and knee pitch joints locked straight down, adjacent legs would use their tools to amputate the failed limb.

One of the most important tasks is the sorting and analysis of science samples. During the LAT-2 process, the science community emphasized that the number of returned samples will be only perhaps 10% of the number that can be collected based on Apollo experience. As a result, it is crucial to have a secondary sorting and "high-grading" process that decides which samples or sub-samples should be returned to Earth. Many in the science community are averse to bringing the samples into a habitat for such purposes, since maintaining them in a pristine, uncontaminated state is of high priority. Thus the science community requested that some sort of robotic capability for this purpose be studied [8]. One way to do this is to have Robonaut work at a robotic workbench having analytical instruments and some means to cleave fresh surfaces off the rocks, together with ATHLETE working to retrieve and perform non-dexterous manipulation to maintain a large organized array of sample containers deployed around the underside of the mobile habitat.

3. MOBILE HABITATS

In the past year, the ATHLETE team (in consultation with the habitat team led by Larry Toups of JSC) created two "micro-habitat" mockup shells (Figure 4) that are small enough that they can be carried by the existing ATHLETE SDMs but are large enough that human occupancy is reasonable. The shells are made of graphite composite and are 2.34 m in diameter and 3.66 m long. Each has an aluminum honeycomb floor (Figure 5), "ring frames" that allow other outfitting (especially soft-goods such as hammock-style bunks or bags of provisions) to be suspended, and solid-state programmable-color lighting.

During field testing at Moses Lake, WA in June 2008 a series of tests was conducted with the habitat mockups mounted on the ATHLETE SDMs. One was a series of hatch-mating tests (Figure 4, bottom) that identified the capability of the system to precisely align mating hatches as would be required on the moon. Because the ATHLETE mobility system has so many degrees-of-freedom, it is capable of moving each of the habitats in any direction or rotating around any axis. The smallest useful increment of motion is about 25 microns, which gives finer control than is really needed for this task. It was found that the accuracy of mating is limited primarily by the patience of the operator, taking some 25-40 minutes to maneuver the vehicles from many meters apart to a mated condition with the hatches aligned typically within a few millimeters. High definition cameras mounted on the top and side of the hatch were used to view alignment marks at the hatch interface to accomplish the precision mating. Typical Earth-moon communication satellite relay time delays of 5-10 seconds were inserted into the command link. No autonomy was used to accomplish the mating, although it is clearly quite feasible to do so. (Autonomy is not enabling for most lunar operations because astronauts will normally be there at the worksite, or

Figure 4: ATHLETE prototypes with habitat mockups during field testing at Moses Lake WA, June 2008.

Figure 5: Inside of habitat mockups, with aluminum floor and "ring frames" for mounting other outfitting.

human operators can use a "move and wait" strategy for operation from Earth without serious negative impact on operations.) One beneficial feature of ATHLETE for the hatch-mating task is that, once the vehicles are in approximately the right position for hatch mating, the wheels can be locked and planted in a single place, so that no terrain shape or properties affect the final docking process. Other tests conducted at Moses Lake included long-range traverses (Figure 4, top), with a combined traverse distance of almost 9 km for both vehicles, and with a longest single traverse of 1.8 km.

Since LAT-2 concluded in the fall of 2007, the Constellation Lunar Architecture Team (CxAT-Lunar, led by Kent Joosten of JSC) and the Constellation Lunar Surface Systems Project (led by Chris Culbert of JSC) have continued to develop and elaborate architectural concepts for lunar exploration. These concepts (like those of LAT-1 and LAT-2) are meant to provide an "existence proof" that a useful and credible program of lunar exploration could be conducted within the resources that can be landed by the currently-planned Orion crew exploration vehicle, the Altair lunar lander, and their associated Ares-I and Ares-V launch vehicles. Final lunar surface architectural components will be decided only in consultation with international and commercial partners.

Part of this conceptual "existence proof" is to show that it is possible to get payloads up to the presumed Altair capacity of almost 15 metric tons off the lander deck and move them to sites where they are protected from ejecta sprayed by subsequent landing events. Figure 6 shows a sequence that would allow an ATHLETE vehicle to carry a payload off the lander deck (over 6 meters high, as previously mentioned). This particular sequence shows the habitat being walked-off the lander at a 12° slope, about the worst-case observed during Apollo. (A habitat with a random slope of even a few degrees would be essentially unlivable.) Figure 7 shows a sequence that would transport a habitat some considerable distance, emplace it onto the surface, and then retrieve a second habitat from a separate lander, and mate those two habitats together down low to the surface where astronaut access is easy and safe. This ATHLETE configuration may also assist (as suggested by Mike Gernhardt of JSC) in lifting habitats up to the level of an ascent stage on an Altair to allow direct shirtsleeves transfer of crew in or out of the ascent stage. This would make it possible for a single suit malfunction of one arriving crewmember not to force a loss-of-mission abort for the whole crew.

Figure 7 includes the "Tri-ATHLETE" concept, developed independently in support of CxAT-Lunar by two members of the ATHLETE team (Jaret Matthews and Scott Howe) to solve the problem of how to get payloads on and off of ATHLETE. The Tri-ATHLETE concept essentially splits the 6-limbed ATHLETE into two 3-limbed vehicles. Each of the two Tri-ATHLETEs can then "embrace" a rectangular payload module to form a fully functional ATHLETE vehicle. Once the system has traversed to the desired location, the Tri-ATHLETEs can squat to place the

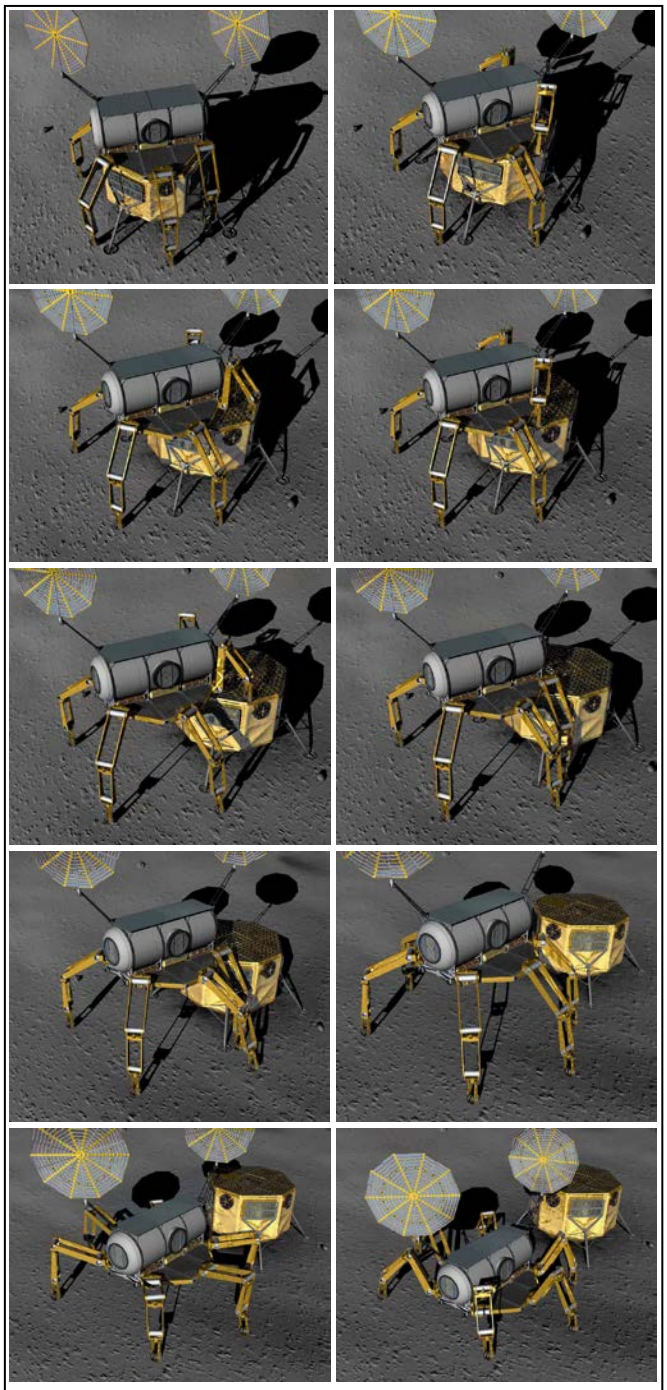

Figure 6: ATHLETE-based cargo/habitat unloading sequence developed for the Constellation Lunar Architecture Team (CxAT_Lunar). Raster scan starting at upper left shows how ATHLETE can walk ~15 ton payload off the lander by stepping only on the nodes of the tubular space-frame making up the Altair lander structure.

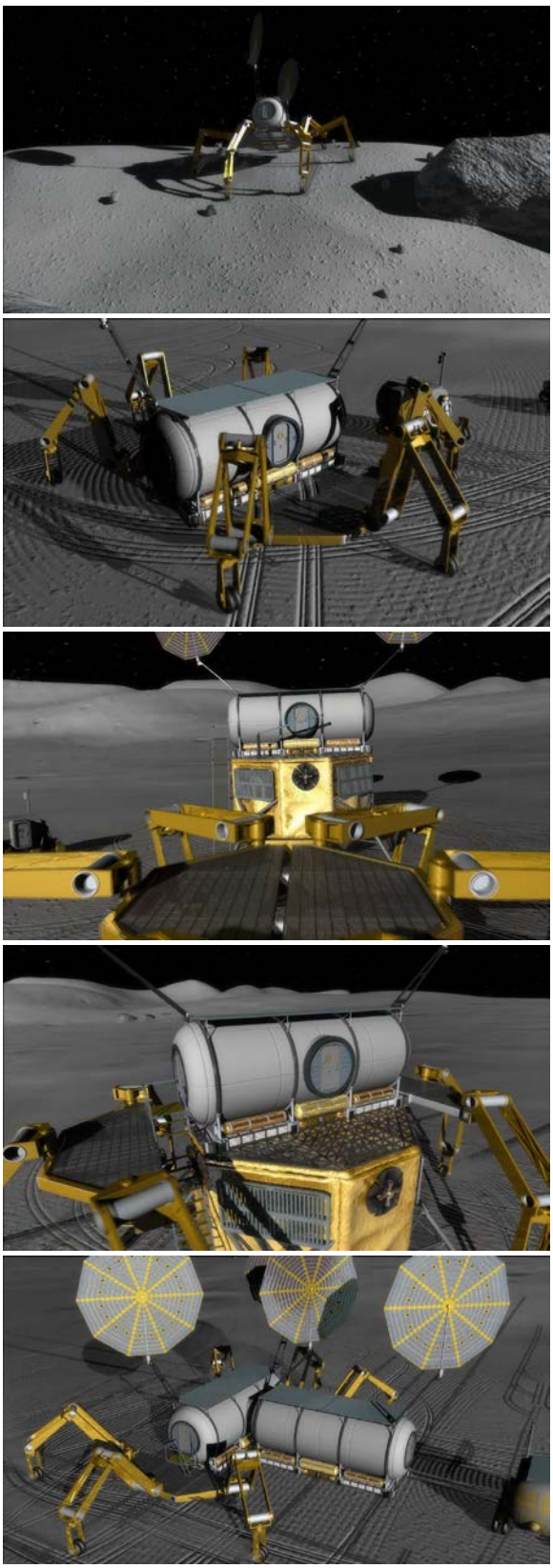

Figure 7: Sequence (from top) to move a habitat to a place remote from landing ejecta; separating "Tri-ATHLETEs" from the main cargo carrier; the Tri-ATHLETEs mate to move to another habitat, dock to its ends, and emplace it "T" connection with prior habitat.

"camper jacks" for leveling), and the Tri-ATHLETEs can then move away as two three-wheeled vehicles. Those three-wheeled vehicles have limited mobility, of course, but they have no payload at that point and so, with their wide stance, should be able to maneuver sufficiently near where any fixed asset would be placed. The two three-wheeled vehicles can use their docking fixtures to attach to each other (without a payload module) for long-distance traverse to pick up a different payload. By having both narrow and wider sets of docking fixtures, the rectangular payload modules can be picked up either along the long or short sides, as depicted in Figure 7.

4. Summary and Conclusions

The ATHLETE team has been working with a progression of lunar architecture definition teams to assist in developing "existence proof" concepts to show that a useful and credible lunar exploration program can be accomplished within the planned capabilities of the space transportation assets: Orion, Altair, Ares-I and Ares-V. The need for extended-range mobility is accepted, as is the need to move payloads (especially habitats) off the cargo deck of the Altair. Mass is at a tremendous premium throughout the architecture. ATHLETE was conceived to be able to provide extreme-terrain mobility at very low mass. This mass savings results from having wheels and wheel drive actuators that are sized for nominal terrain instead of the worst terrain that will ever be encountered. If the rolling vehicle gets stuck (roughly once-per-day), it simply locks the wheels and uses them as feet in walking out of the extreme terrain. The resulting wheels and drive actuators are much lighter than those needed for a conventional vehicle. This mass savings more than makes up for the mass of the limb actuators, while the structure of the limbs has roughly the same mass as the structural elements of a conventional mobility chassis. Each limb of an ATHLETE mobility subsystem is outfitted with a quick-disconnect tool adapter, with a rotating power take-off from the wheel so that a wide variety of tools can be used for science sampling, assembly, maintenance, or repair tasks. Simple tools such as grippers and drills can be used, or a dexterous anthropomorphic robot such as Robonaut. One of the more attractive options with Robonaut is to set up a "robotic workbench" where science samples can be sorted and analyzed to decide which ones should be returned to Earth, as the human astronauts are expected to collect up to ten times as many samples as can be returned.

The "Tri-ATHLETE" concept emerged in support of the Constellation Lunar Architecture Team, allowing ATHLETE to "embrace" a payload and "walk" it off the high deck of the Altair cargo lander, and to provide low-mass, extended-range mobility for that payload, even over extreme terrain. One of the most attractive payloads to make mobile in this way are habitats, which can act as local

bases for radial exploration using small pressurized rovers. This has become known as the "Jeeps and Winnebagos" method of exploration. The mobile habitats would carry large solar arrays and sufficient energy storage (batteries or regenerative fuel cells), "keeping to the high ground" where sunlight is abundant so that the small pressurized rovers can be recharged after each exploration sortie. A pair of such mobile habitats, together with a pair of small pressurized rovers, would provide sufficient resources for global-scale exploration, since if one mobile habitat became immobilized, the second could be used as the mobile power station needed to support a long traverse back to the Altair ascent stage.

5. ACKNOWLEDGEMENTS

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BIOGRAPHY

Brian Wilcox is a principal member of the technical staff in the Autonomous Systems Program Development Office at JPL, 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.