ATHLETE: Lunar Cargo Handling for International Lunar Exploration

Brian H. Wilcox[1]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

As part of the Human-Robot Systems Project within the NASA Exploration Technology Development Program, the Jet Propulsion Laboratory is developing a vehicle called ATHLETE: the All-Terrain Hex-Limbed Extra-Terrestrial Explorer. The basic idea of ATHLETE is to have six relatively small wheels on the ends of legs. The small wheels and associated drive actuators are much less massive than the larger wheels and gears needed for an "all terrain" vehicle that cannot "walk" out of extreme terrain. The mass savings for the wheels and wheel actuators is greater than the mass penalty of the legs, for a net mass savings. Starting in 2009, NASA became engaged in detailed architectural studies for international discussions with the European Space Agency (ESA), the Japanese Space Agency (JAXA), and the Canadian Space Agency (CSA) under the auspices of the International Architecture Working Group (IAWG). ATHLETE is considered in most of the campaign options considered, providing a way to offload cargo from large Altair-class landers (having a cargo deck 6+ meters above the surface) as well as offloading international landers launched on Ariane-5 or H-2 launch vehicles. These international landers would carry provisions as well as scientific instruments and/or small rovers that would be used by international astronauts as part of an international effort to explore the moon.Work described in this paper includes architectural studies in support of the international missions as well as field testing of a half-scale ATHLETE prototype performing cargo offloading from a lander mockup, along with multi-kilometer traverse, climbing over >1m rocks, tool use, etc.

I. 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 NASA Johnson Space Center (JSC). ATHLETE was conceived to transport large masses (cargo and habitats) on the moon [1]. Two approximately quarter-scale prototype "Software Development Model" (SDM) vehicles were built and tested between 2005 and 2009 (Figure 1). The SDM vehicles were built with hexagonal frames 2.75 m across, with each of the 6-degree-of-freedom limbs standing a maximum of 2.08 m at the hip pitch axis. 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 (identical 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 Marshall Space Flight Center, with supporting team members drawn from NASA headquarters and many of the NASA field centers (including this author). The original LAT results were presented at the 2nd AIAA Conference on Space Exploration in Houston TX, Dec 4-6, 2006 [2]. LAT recommended that mobile landers be studied in the next phase of the LAT process. That next phase, LAT-2, was led by astronaut 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 [3]. This LAT-2 out-brief concluded that

[1] ATHLETE Principal Investigator, Autonomous Systems Architecture Office, 4800 Oak Grove Dr M/S 303-300, Member, AIAA.

- "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 [a] different site and awaits arrival of next crew."

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

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

II. 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 never be permitted to get stuck. Vehicles in the latter category (current Mars rovers are good examples) must be able to successfully traverse perhaps 99.99% of the surface, so that one could reasonably expect them 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.

Soil mechanics studies [4] indicate that a wheel that only rolls over the "2-σ softest" terrain (e.g. 97% of all terrain) can tolerate about four times as much ground pressure as one that must be able to successfully roll over the "4-σ softest" terrain (e.g. 99.99% of all 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 dimension). Since the wheel contact patch area increases with the square of the dimension, the change 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. The requirement derives from the fact that up to half the weight of the vehicle may project onto the one wheel down in the hole, and that wheel may need to climb nearly vertically out of the hole. 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 27-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, so approximately 90% of the drive gear mass is saved. 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. Stall torque requires half the weight of the

vehicle in rim thrust, while normal running rim thrust for each wheel is only about 1-2% of the total vehicle weight. This 25-to-50-to-1 ratio between stall and running torque is not consistent with the 2-or-3-to-1 working ratio common in brushless motors, while for ATHLETE the motors are designed to operate near their continuous max-power points. The combined savings in mass associated with the smaller wheels, the lower-torque wheel drive actuators, and the more efficient operation 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 [5].

Figure 2 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 the tool. This can be direct mechanical power, as seen in Figure 2a 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 (Figure 2b). 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 visualization 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 ATHLETE limb actuators fail, usually the leg retains some limited capability. In the worst-case failure where the hip pitch and knee pitch joints are locked straight down, adjacent legs would use their tools to amputate the failed limb, and the vehicle continues as a 5-wheeled vehicle.

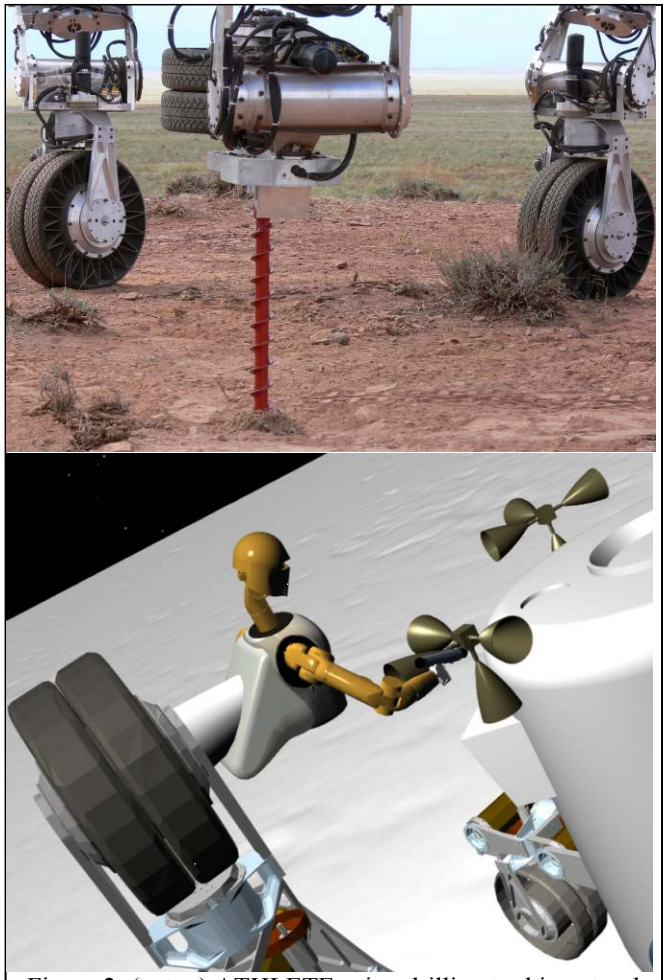

Figure 2: (a, top) ATHLETE using drilling tool in natural terrain, (b, bottom) ATHLETE using Robonaut anthropomorphic robot developed by the Johnson Space Center for tasks requiring human-like dexterity.

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, because the Orion return mass is limited. 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 [6]. 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, e.g. to maintain a large organized array of sample containers deployed around the underside of a mobile habitat.

III. Summary of Previously-Reported Results

In 2009, a half-scale ATHLETE vehicle was built, approximately twice the size of the previous prototype (Figure 3). This system actually consists of two "Tri-ATHLETE" vehicles, docked together with a modular cargo

pallet sandwiched between them. The Tri-ATHLETE concept [7] allows ATHLETE to pick up and set down cargo pallets without needing to "limbo" out from under them. This is accomplished by splitting the hexagonal frame of ATHLETE into three pieces - a center rectangular interchangeable cargo pallet, and two triangular "wings" that each have three of the limbs attached. These wings, each with three limbs and wheels, have been dubbed "Tri-ATHLETEs". The cargo pallet we are working with (a mockup of the "Power Support Unit" as developed by the NASA Constellation Architecture team) contains the passive side of the docking fixtures, and provides long-term power to both the payload (a habitat mockup in our current tests) as well as to the Tri-ATHLETEs.

Figure 3: Half-scale ATHLETE built in 2009, with author for scale.

Figure 4: Other activities conducted at Black Point included (top) use of tools, such as drills, grippers, and scoops to take samples of terrrain and manipulate containers, and (bottom) joint experiments with the Lunar Electric Rover, with astronauts directly operating ATHLETE both for mobility and manipulation from within the LER.

The main objective of our work in FY 2009 was to develop the system to the point where a cargo offloading demonstration could be conducted from a half-scale Altair lander mockup (Figure 4). This test was performed, first at JPL in our lab and subsequently at the NASA "Desert Rats" analog field test conducted at Black Point near Flagstaff AZ for three weeks in September 2009.

Other activities conducted at the Black Point field test (Figure 4) included use of tools such as a drill, gripper, and scoop to collect samples and to manipulate containers. Crew operated ATHLETE for both mobility and manipulation from within the Lunar Electric Rover (which itself was used for a continuous 14-day test of crew operating as if they were on the moon, staying within the LER or outside during Extra-Vehicular Activities using simulated space suits.

IV. International Collaboration

Periodically throughout 2009 and the first half of 2010, the International Architecture Working Group (IAWG) met under the auspices of the International Space Exploration Coordination Group (ISECG). Organizations involved in ISECG include ASI (Italy), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (European Space Agency), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of

America), NSAU (Ukraine), Roscosmos (Russia), UKSA (United Kingdom). Active participants in the development of a reference architecture included NASA, ESA, JAXA, and CSA. Other ISECG member institutions participated in some (many, in some cases) of the meetings. The ATHLETE team was represented at such meetings in the Netherlands, Canada, and in the U.S.

The "ISECG Reference Architecture for Human Lunar Exploration" was finalized in the first half of 2010. The architecture is proposed to have multiple phases [8]:

- ***robotic precursor phase****: This phase provides early technology demonstrations and engagement among international partners, the scientific community and the public. It highlights important activities intended to reduce the risks associated with human missions and to ensure sustainability of the architecture. These activities will also help target human missions toward the most promising objectives for scientific discovery and exploring Mars.*
- ***polar exploration and system validation phase****: This phase initiates human exploration of the Moon. It leverages the robotic precursor work to deploy and test an international fleet of crew rovers and supporting robots in preparation for more aggressive human and robotic lunar exploration. This phase builds up confidence in operations and systems design through a series of human missions at a given lunar polar site.*
- ***polar relocation phase****: In this phase, the fleet of robots and rovers, controlled from Earth, will be relocated from the pole to new sites of interest. Along the way, they will perform scientific studies and enable interactive participation from the public. Once in place, they will meet and assist human crews landing at these new sites.*
- ***non-polar relocation and long-duration phase:*** *This phase may involve multiple short missions to various lunar sites of interest or long-duration missions of about 70 days at one site. Longer missions, which will require the addition of living modules or habitats, would be particularly useful for collecting data and testing technology for future Mars missions.*

V. A Fleet of Robots and Rovers

The key concept of the ISECG reference architecture is a "fleet of robots and rovers" (described above in the "polar relocation phase"). This fleet would move robotically over the lunar surface during the time between human missions so as to arrive at the next landing site. In this way, all prior landed assets can be used by each successive crew at their exploration site. This is a significant advance over the Apollo missions of 40 years ago, where all landed assets from each mission were abandoned on the surface, unused by future missions. A major element of this concept is that international landers launched by ESA on the Ariane-5 or JAXA on the H-2 can land along the route of the international fleet of robots and rovers. These landers can deliver science instruments, additional robotic rovers, and provisions such as food, water, oxygen, and batteries. These payloads can be picked up by and incorporated into the mobile fleet, becoming available for use by subsequent crews. In this way, with no exchange of funds between the various space agencies, significant extra provisions can be provided to "close" the architecture in a way that the planned U.S. Altair lunar lander could not economically accomplish, and also individual national space agencies can deliver dedicated science instruments of their own choosing for (possibly exclusive) use by their astronauts on the moon.

Shown in Figure 5 is a sequence of images from the video "trailer" developed for the ISECG Reference Architecture. This sequence illustrates an important feature of this architecture - that larger vehicles such as ATHLETE can carry smaller robotic systems during long-range traverses. In this sequence, an ATHLETE vehicle uses its tool-adapter capability to pick up and stow on its back a smaller "centaur-like" robotic rover having a humanoid torso on a wheeled base frame. This smaller rover would be extremely useful for assembly and maintenance tasks, but would benefit greatly if it could be carried long distances between exploration sites, instead of having to drive long distances on its own. In particular, the ATHLETE vehicle carries a payload with very large solar arrays and energy storage (batteries or regenerative fuel cells), so that it has the needed power for long traverses. Smaller vehicles are greatly challenged by power collection and energy storage in making long traverses on their own. The summary document describing the ISECG Reference Architecture [8] identifies the ATHLETE flight system as being developed during the Polar Exploration and System Validation Phase (Figure 5 of reference [8]), so that they are available at the beginning of the Non-Polar Relocatability Phase - e.g. in time to support global international exploration of the moon.

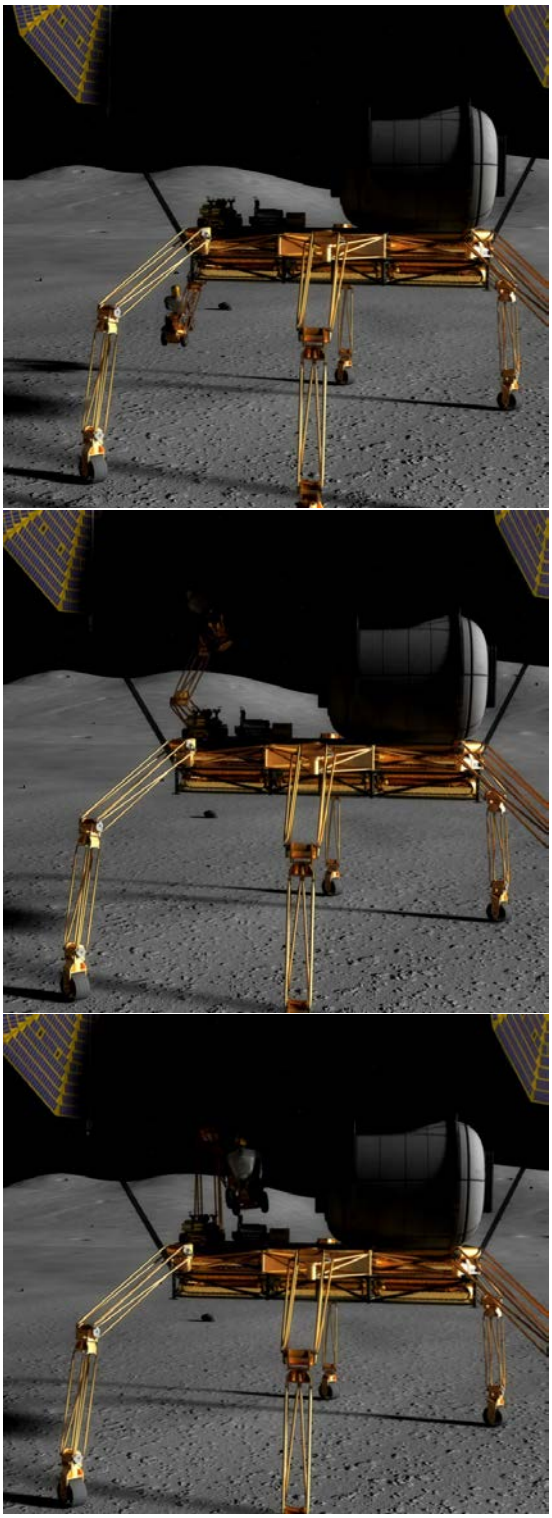

Figure 5: Series of images (from top) depicted in ISECG video "Trailer" describing the Reference Architecture for Human Lunar Exploration, showing ATHLETE picking up and stowing a smaller robotic rover in preparation for a long-distance traverse.

VI. Conclusion

The ISECG effort to define a Reference Archecture for international human exploration of the moon has been "overtaken by events." Specifically, in February 2010 the new U.S. Administration proposed a NASA budget for Fiscal Year 2011 that eliminated human lunar return as a near-term objective of U.S. space policy. The "Augustine Commission," reviewing the U.S. human spaceflight program, had observed that Mars is the ultimate target for human exploration in the inner solar system. They defined a "Flexible Path" which initially would send humans to Near-Earth Objects, practicing the extended deep space operations needed for future human missions to Mars. However, they point out "exploration along the Flexible Path would not likely complete our preparation for the exploration of Mars. At some point we would likely need to gain more experience landing and working on an extra-terrestrial planetary surface. This could be done on the Moon with specialized lunar systems..." [9, p43]. So human missions to the moon in preparation for exploration of Mars are not ruled out.

On 15 April 2010 President Obama gave a speech at the Kennedy Space Center in Florida committing to sending humans to a Near-Earth Object by 2025. As of this writing (July 2010) one committee of the U.S. Senate has passed a version of a NASA budget that calls for building a heavy-lift launch vehicle and a deep-space-capable human capsule that would be suitable for missions to NEOs, the moon, and can perhaps Mars.

The ATHLETE team has been working with a progression of architecture definition teams to assist in developing "existence proof" concepts to show that a useful and credible space exploration program can be accomplished. The need for extended-range mobility has been accepted by these assorted architecture teams for lunar or Mars exploration, as is the need to move payloads (especially habitats) off the cargo deck of a lander. Mass is at a tremendous premium throughout the architecture. ATHLETE was conceived to be able to provide extreme-terrain cargo 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.

One of the most attractive uses of ATHLETE is as part of a "fleet of robots and rovers" that move substantial distances between successive human landing sites on the moon or Mars. In this way, all previously-landed assets can be made available to each human crew, overcoming the extreme inefficiency of an Apollo-like architecture where every mission must bring all that they need with them. A particular advantage comes when landers launched by International Partners can arrive along the path of the robotic fleet. This helps "close" the architecture with respect to mass of provisions, and can also allow individual national space agencies to deliver science instruments, small rovers, and other equipment for use by their astronauts as part of an international program of exploration of the moon or Mars.

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The original core ATHLETE team members are listed in [1]. Additional members who have joined since inception are Matthew A. Frost, Curtis L. Collins, Lee J. Magnone, John M. "Jack" Dunkle, Michael C. McHenry, Thomas I. Valdez, Joseph C. "Chet" Joswig, Christopher McQuin, David S. Mittman, Jeffrey S. Norris, Mark W. Powell, Nicholas T. Toole, Recaredo J. "Jay" Torres, John R Wright, and A. Scott Howe. Robert O. Ambrose and the Robotnaut team (at the NASA Johnson Space Center) supplied the rendering in Figure 2b. Computer renderings in Figure 5 were created by Bob Evangelista, David Helton, Jeffrey Murch, Joshua Sams, and Rob Burns of Analytical Mechanics Associates, Inc. under the direction of Pat Troutman of the NASA Langley Research Center.

References

[1] Wilcox, Brian H, Litwin, Todd E., Biesiadecki, Jeffrey J., Matthews, Jaret B., Heverly, Matthew C., Morrison, Jack C., Townsend, Julie A., Ahmad, Norman M., Sirota, Allen R., and Cooper, Brian C. "ATHLETE: A cargo handling and manipulation robot for the moon", Journal of Field Robotics, Volume 24 , Issue 5 (May 2007) Special Issue on Space Robotics, Part III, Pages: 421 - 434.

[2] The conclusions of the original Lunar Architecture Team were presented at the 2nd AIAA Space Exploration Conference, Houston TX, Dec 4-6 2006. See http://www.aiaa.org/ content.cfm?pageid=230&lumeetingid=1487&viewcon=other657&id=657 for details, last accessed 27 June 2009.

[3] The conclusions of the LAT-2 were presented at the AIAA Space 2007 Conference, Long Beach, CA September 18-20 2007. A copy of the presentation is at http://www.spaceref.com/ news/viewsr.html?pid=25506, last accessed 27 June 2009.

[4] Wilcox, B. "ATHLETE: An Option for Mobile Lunar Landers", proc. IEEE Aerospace Conference, Big Sky, MT March1-7, 2008, paper 1-4244-1488-1/08. (#1376).

[5] Snook, K. "Outpost Science and Exploration Working Group (OSEWG)", presentation to Planetary Science Subcommittee, chart 10. March 4, 2008. Available at http://www.lpi.usra.edu/pss/presentations/200803/13-Snook-OSEWG.pdf, last accessed 27 June 2009.

[6] Albus, J., Bostelman, R., and Dagalakis, N., "The NIST SPIDER, a Robot Crane", Journal of Research of the National Institute of Standards and Technology, 97:33, pp 373-385, National Institute of Standards and Technology, 1992. Available at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/ 19930018791_1993018791.pdf, last accessed 27 June 2009.

[7] Wilcox, B.H. " ATHLETE: A Cargo and Habitat Transporter for the Moon", proc. IEEE Aerospace Conference, Big Sky, MT, 7-14 Mar 2009, paper 978-1-4244-2622-5/09 #1417.

[8] Summary Report, "The ISECG Reference Architecture for Human Lunar Exploration", *ISECG International Architecture Working Group, July 2010.* Available at http://www.globalspaceexploration.org/c/document_library/ get_file?uuid=7cb7e62e-b2a5-4dfe-9da8-25043a4f5145&groupId=10812, last accessed 26 July 2010.

[9] Augustine, Norman et al, "Review of U.S. Human Spaceflight Plans Committee," available at http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf.