ATHLETE: A Limbed Vehicle for Solar System Exploration

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Abstract— As part of the Human-Robot Systems project funded by NASA, the Jet Propulsion Laboratory has developed a vehicle called ATHLETE: the All-Terrain Hex-Limbed Extra-Terrestrial Explorer.[1] Each vehicle 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 for nominal terrain. There are substantial mass savings in the wheel 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. A side benefit of this approach is that each limb has sufficient degrees-of-freedom to 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 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.

This paper describes the applicability of the ATHLETE concept to exploration of the moon, Mars and Near-Earth Asteroids (NEAs). Recently, the focus of human exploration beyond LEO has been on NEAs. One scenario for exploration of a NEA has been likened to a submarine exploring a wrecked ship - humans would sit in a "bubble" and approach the asteroid for up-close examination and robotic manipulation. What is important is to ensure that the bubble doesn't collide with the asteroid surface, nor float away. Multiple limbs, such as available on ATHLETE, allow for precise positioning and anchoring so as to enable the human bubble to maximize its exploration potential. A microgravity testbed has been constructed in the ATHLETE lab, with six computer-controlled winches able to lift ATHLETE and payloads so as to simulate the motion of the system in the vicinity of a NEA. Accurate 6-axis force-torque sensors will measure the applied forces and moments wherever the vehicle touches a simulated asteroid surface. These measured forces can be used to compute the resultant motion of the vehicle in the microgravity environment, and the winches then move the vehicle along the computed trajectory. Preliminary test results from this system are described.
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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 and Bill Bluethmann of the NASA Johnson Space Center (JSC). ATHLETE was conceived to transport large masses (cargo and habitats) on the moon [2]. 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 tall 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 to 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 team studied ways to implement Human Lunar Return (HLR) that had been identified as a key objective of the "Vision for Space Exploration" [3].

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

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

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 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 [5]. This LAT-2 out-brief concluded 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 [a] 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 planetary 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 ATHLETE to get "stuck" while rolling once or twice a day, since it can simply walk out of such extreme terrain.

Soil mechanics studies [6] indicate that a wheel that can roll efficiently 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 yields half the weight of the vehicle in rim thrust, while normal running rim thrust 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 efficient range common for brushless motors, while for ATHLETE the motors generally operate near their continuous peak-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 [7].

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 3b). Complex end-effectors 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 can "feel" 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, generally the leg retains some reduced 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.

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 crew return capsule Earth-entry mass is so limited. As a result, it is crucial to have a secondary sorting and "high-grading" process that selects 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, e.g. to maintain a large organized array of sample containers deployed around the underside of a mobile habitat.

3. SUMMARY OF PREVIOUSLY-REPORTED RESULTS

In the previously mentioned architecture studies the assumed lander uses liquid oxygen and liquid hydrogen propulsion for the descent stage. This, together with the fact that (unlike Apollo), in the Constellation architecture, the descent stage was conceived to perform the lunar orbit capture maneuver, means that the liquid hydrogen tanks in particular are especially large (due to the low density of LH_2 - only 71 kg/m^3). As a result, the deck of the "flat top" configuration of the "Altair" lander that has received the

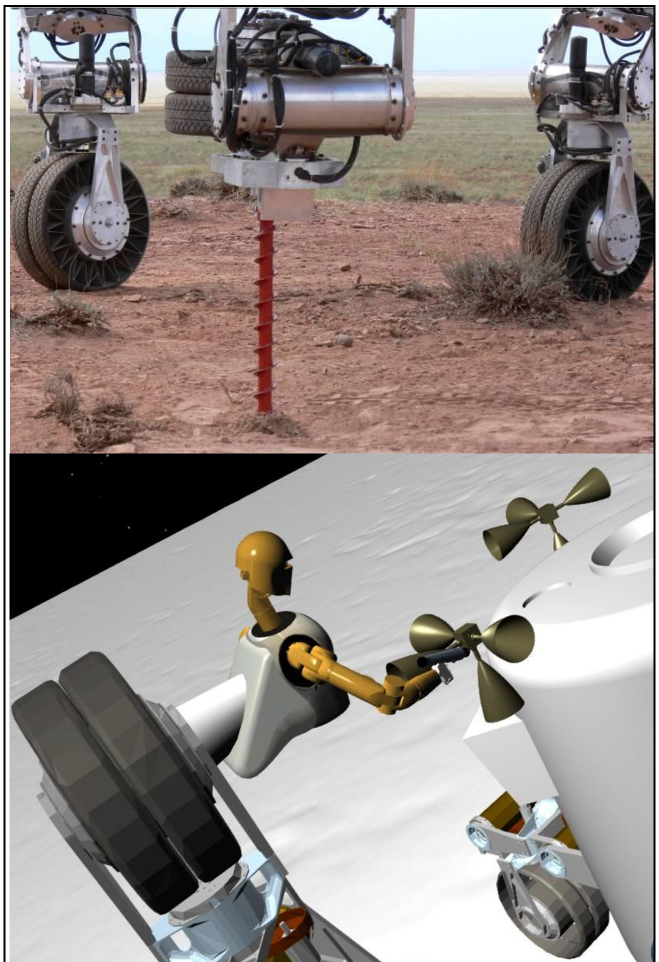

Figure 2: (a, top) ATHLETE using drilling tool in natural terrain, (b, bottom) ATHLETE using Robonaut anthropomorphic robot developed by the Johnson Space Center for tasks requiring human-like dexterity.

most analysis to date is just over 6 meters above the lunar surface after landing.

The sheer height of this deck has alarmed some observers as posing a difficult or impossible challenge for offloading cargo. In 2009, a half-scale ATHLETE vehicle was built (Figure 3), approximately twice the size of the previous prototype. This system actually consists of two "Tri-ATHLETE" vehicles, docked together with a modular cargo pallet sandwiched between them. The Tri-ATHLETE concept [11] 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 contains the passive side of the docking fixtures, and provides long-term power to both the payload (a habitat or pressurized logistics carrier mockup in our current tests) as well as to the Tri-ATHLETEs.

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, approximately 60 km north of Flagstaff AZ, for three weeks in September 2009.

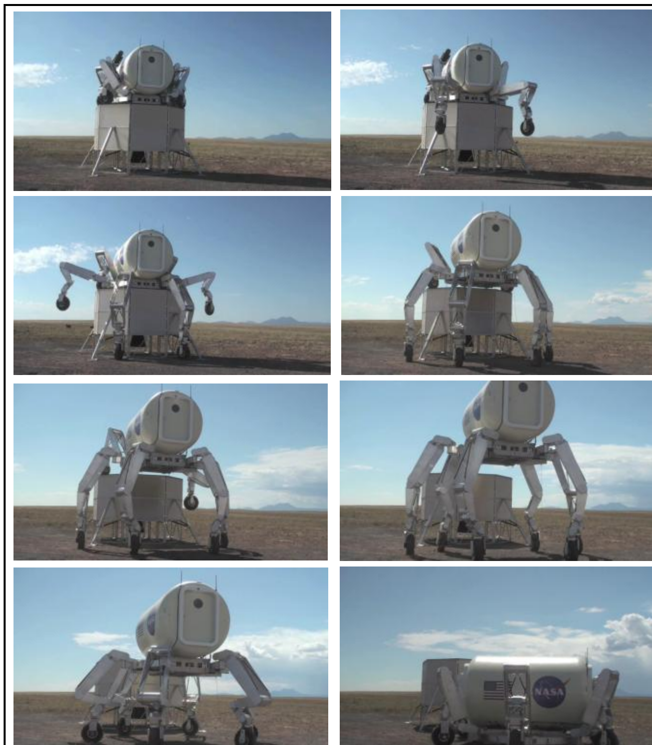

Figure 4: ATHLETE-based cargo/habitat unloading sequence performed at the NASA "Desert Rats" analog field test in Sep 2009. Raster scan starting at upper left shows ATHLETE unloading half-scale payload off a lander mockup by stepping only on the nodes of the simulated tubular space-frame making up the Altair lander structure.

In August-September 2010, a more ambitious field test was conducted, again at Black Point. The primary objectives of the ATHLETE portion of the test was to conduct a long traverse, demonstrating the key operational features that ATHLETE brings to the planetary exploration architecture: the ability to transport cargo such as habitats or pressurized logistics carriers to rendezvous with crew at predetermined points, and to keep mostly "to the ridgelines" where solar power is abundant to stockpile energy that can be used to recharge other vehicles and where the system can function as a communication relay for all the mobile assets.

A total of 63 km of traverse was conducted by ATHLETE during the 2010 DRATS field test, mostly cross-country from a base camp on the Black Point lava flow to a temporary exploration camp set up near SP Mountain, a volcanic cinder cone approximately 20 km WSW of the base camp. At the temporary camp, a habitat mockup known as the Habitat Demonstration Unit (HDU) was emplaced, where the MultiMission Space Exploration Vehicles (MMSEVs, formerly known as Small Pressurized Rovers or Lunar Electric Rovers) could conduct human exploration trials in the rugged volcanic terrain.

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

4. DEVELOPMENTS IN 2011

In February 2010 the Administration announced the new FY'11 NASA budget proposal calling for the termination of the Constellation program seeking to return humans to the moon by 2020, and in April 2010 the President gave a speech at the Kennedy Space Center in Florida proposing that NASA explore a Near-Earth Asteroid (NEA) with humans by 2025.

Typical NEAs that could be reached within reasonable time by near-term human space systems (e.g. similar to the Orion Multi-Purpose Crew Vehicle and Space Launch System heavy-lift launch vehicle) have a diameter of only about 100 meters. Their surface gravity, being proportional to radius and density, is only a few micro-g, and they frequently spin such that the centrifugal force at the equator is comparable to the gravity. Those that have been imaged often show an extremely irregular (e.g. potato-like) shape, so the gravity field is highly non-radial. About 10% of the population is tumbling, i.e. the angular momentum has not settled into alignment with the axis of maximum moment of inertia.

These considerations make human exploration of such objects challenging. A human, exerting 1% of normal standing force on Earth, would push off with escape velocity in less than half a second. The complex non-radial gravity field and rotating reference frame dynamics will make navigation highly non-intuitive.

We have created a low-gravity testbed (Figure 5 and 6) suspended by six cable winches to a frame near the ceiling of a high-bay. The six winches can move the platform in any of the six degrees-of-freedom: x, y, z, roll, pitch, and yaw.

The low-gravity testbed has a work platform (Figure 7) that is suspended by six cables from three towers (Figure 8) with swiveling sheaves (Fairleads) that allow the cables to move smoothly independent of where the work platform is in the workspace. The cables emanate from pairs of winches (Figure 9) at the base of each tower, each equipped with a ~10hp brushless motor. Figure 10 shows detail of the six struts that connect ATHLETE to the work platform.

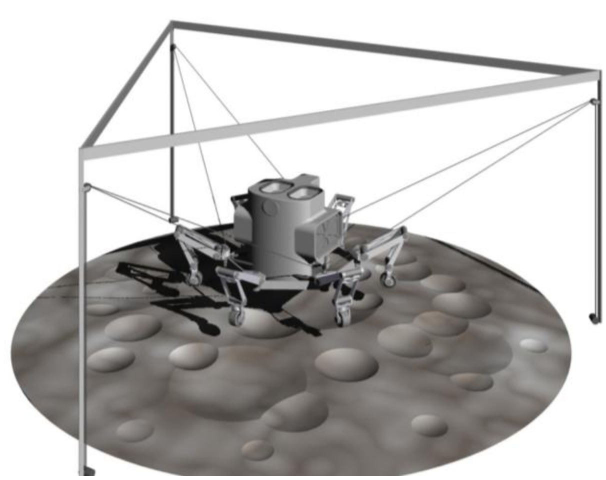

Figure 5. Suspended platform for simulated low-gravity operations at Near-Earth Asteroids.

Figure 6. ATHLETE suspended by six computer-controlled winches, giving control in x, y, z, roll, pitch, and yaw over a ~3 m work volume.

Figure 11 shows a simulated "hop" in a gravity field of 5 microgees. In the first picture (at the top) ATHLETE crouches down in preparation for the hop. In the second photo, the ATHLETE limbs have pushed down and the wheels have left the surface. In the third and forth pictures, ATHLETE is at various stages of the parabolic arc, reaching a height of approximately 2 meters. In the bottom picture, ATHLETE touches down with one of its wheels. This is the last image since realistic modeling of the events after first contact await installation of precision force-torque sensors at the "ankles" of each of the limb early in FY 2012. The precise location of the work platform is tracked by a commercial Vicon motion capture system that uses six widely-spaced infrared cameras to precisely locate a large number of retroreflectors distributed over the work platform. This position is used as the primary feedback for the winch controllers. Position encoders on the winches, and force sensors at the attachment points of the six cables to the work platform are used primarily as safety backups.

Figure 12 shows a "Hollywood asteroid" mockup purchased from a local prop house supporting the video and film industry. It is made of foam and plastic "bed liner" used to line the beds of pickup trucks. In 2012 we plan to perform proximity operations testing using this mockup for stereo vision and/or laser ranging sensors to determine relative pose and velocity.

Figure 13 shows simulated anchoring into the loose regolith of a NEA. Two counter-rotating augers prevent any torque-reaction to the vehicle in microgravity. The augers each have only two widely-space flutes, which give good holding force while reducing the required emplacement power [12].

5. PLANS FOR 2012

The work platform of the low-gravity testbed allows ATHLETE components to be flown together or as a "tool kit" - having three to six landing feet with anchoring devices

Figure 7: Work platform, suspended by 6 cables, with force sensors on swivels in series with cables.

such as the helical auger previously discussed, or a rotary-percussive drill or a harpoon. An auger or harpoon would be used if the NEA surface were loose regolith or turned out to be the "fairy castle" dust remnant surface of an extinct comet. A rotary-percussive drill would be used for bare rock surfaces of monolithic rock asteroids, which are presumed to be a large fraction of the population of small NEOs (since they are often spinning faster than the "rubble pile limit" where centrifugal force is greater than gravity force at the equator [13]. Magnets would be used to anchor to nickel-iron asteroids, although they are generally not sought as an exploration target for human or scientific missions. The axial force needed for percussive drilling would be provided by brief thrust from the simulated reaction control system of the platform. Six-axis force sensors at the ankles will allow the winches to simulate the statics and dynamics of both landing and free-fall. The low-gravity platform testbed will be suspended over terrain simulant that includes representatives of all the types of surface that seem plausible, equipped with terrain sensors such as flash LIDAR or other 3-D range imaging device so that time-to-contact can be estimated, and the appropriate pose for contact computed..

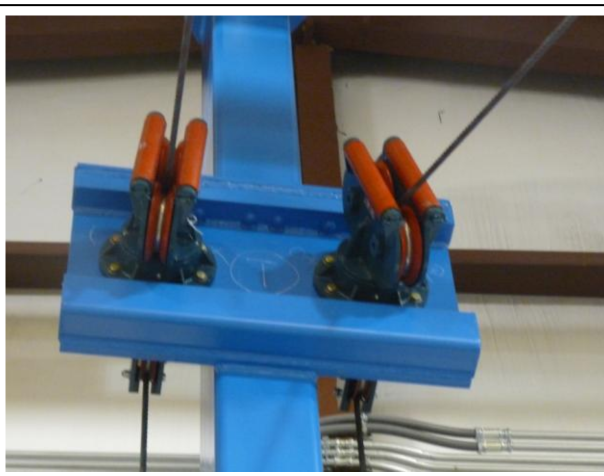

Figure 8: Sheaves and Fairleads at top of towers that manage steel cables suspending work platform.

Combined with the low-gravity testbed platform will be a flight simulator- type virtual environment cockpit, where the human operator could sit and "fly" the platform as if he or she is at a NEA. They would see 3-D images in real-time from the platform, and displays also showing the 3-D ranging sensor results, the navigation system status, and vehicle state data such as equivalent propellant consumed. When the navigation assist is turned off, the operator will experience the highly non-intuitive gravity and rotation dynamics and the great difficulty of reaching any particular target spot. With the navigation assist turned on, the operator will have intuitive joystick control mapped into an inertial reference frame. Other assist, such as automated hazard and target-relative navigation to touchdown will be provided. Upon touchdown, either the darts or the drills will engage and anchor to the target. The use of "real" sensor data will overcome the old adage that "simulations are doomed to succeed" when synthetic sensor data substituting for the complex contact physics associated with

Figure 9: Computer-controlled 10 hp brushless winches used to actuate low-gravity testbed.

natural terrain are used to feed purely analytical simulations. This system could simulate a vehicle that can carry one or more astronauts (in space suits, or "man-in-a-can modules", or two-person pods such as the MMSEV) to sites of scientific interest safely and intuitively, and upon arrival can anchor there so that scientific measurements and samples can be collected. The ATHLETE limbs can be used with or without wheels. Without wheels, they would have instrumented landing pads that measure the six components of force and torque imparted to the terrain for use in simulating the rebound and dynamics of the vehicle using the six cable winches. With wheels, similar forces are torques would be measured and the dynamics simulated, with rolling mobility used to make precision approaches to points of interest on the asteroid surface.

6. SUMMARY AND CONCLUSIONS

ATHLETE was conceived to be able to provide extreme-terrain cargo mobility over planetary surfaces 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 (e.g. roughly once-per-day), it simply locks the wheels and uses them as feet in walking out of 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 allows 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

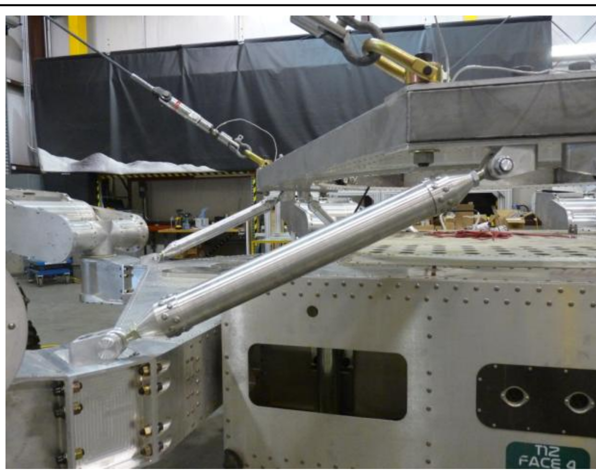

Figure 10: Attachment detail of ATHLETE to work platform.

Figure 11: Sequence showing ATHLETE making a 5 microgee "hop" to a height of almost 2 meters using the low-gravity testbed. Numbered from top 1) crouch, 2) jump, 3) near apex, 4) beyond apex, 5) assume landing pose, and 6) touchdown.

Figure 12: "Hollywood" asteroid, ~8 m on a side and ~2 m high.

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 ascent stage.

In FY'11 the ATHLETE testbed system was extended to near-Earth asteroid mission simulations by suspending it using six computer-controlled winches to emulate micro-gravity operations over a simulated asteroid surface. In FY' 12, contact forces and torques will be precisely measured to allow computation of the correct motion of the vehicle in microgravity during and after contact events, which will be achieved by actuation of the winches. Rolling mobility will be used to achieve precise approach to targets of interest. An "immersive" operator control station will allow the human operators to become familiar with operations in the non-radial gravity field and rotating/tumbling dynamics of a NEA.

7. ACKNOWLEDGEMENTS

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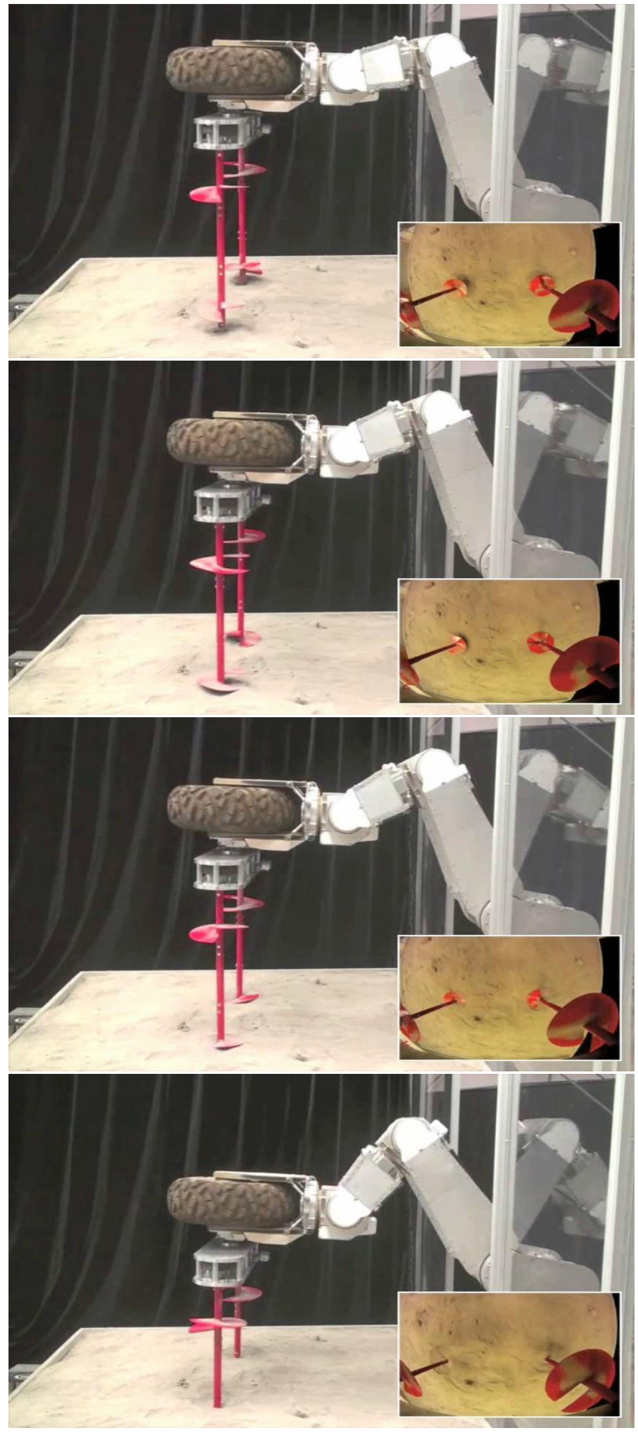

Figure 13: Sequence showing use of auger-type anchor on soft simulant representing asteroid regolith. Numbered from top 1) preparing to anchor, 2) touching auger to surface, 3) first flute disappears into regolith, 4) as deep as test bin will allow.

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BIOGRAPHY

Brian Wilcox is 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.