ATHLETE: Lunar Cargo Unloading from a High Deck

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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] 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 at least 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 lighter than a conventional all-terrain mobility chassis. A side benefit of this approach is that each limb has sufficient degrees-of-freedom to be used 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.

Architectural studies have indicated that one 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 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 it requires very large tanks. A natural geometry for the lander is to have a single throttleable rocket engine on the centerline at the bottom, and to have the propellant tanks arranged as compactly as possible around and above that engine, with nearly-straight structural load paths that carry the heavy LO_2 tanks as well as the ascent stage or cargo on a top deck. (The requirement for exactly one descent engine stems from the need to avoid symmetry planes in the exhaust plume that can entrain surface particles and loft them up into the system at hypervelocity.) This geometry is especially attractive since abort considerations drive the ascent stage to have as much open space around it as possible, in case the ascent stage needs to launch away from an out-of-control descent stage. These considerations lead to a configuration where the cargo deck of the lander is relatively high off the ground (over 6 meters in current concepts, using a 10-meter diameter launch shroud). This nominal configuration has led some observers to presume that there is a "lander offloading problem".

Fortunately, the lunar gravity is very low. Consider a "mobile scaffolding," analogous to those used for cargo handling in any harbor as required for stacking shipping containers or drydocking boats. Such a system might have a vehicle mass comparable to its payload in Earth's gravity, but will have a mass that is only about 10% of the payload in lunar gravity (if 1 unit of vehicle mass can carry 1 unit of payload in Earth gravity, then it can carry 11 units of payload in 1/6th gravity). Endowing that mobile scaffolding with extreme-terrain mobility appropriate for the moon only increases its mass to about 15% of the payload mass. ATHLETE can be viewed as an example of such a mobile scaffolding. ATHLETE has limbs sufficiently long that it 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. Because ATHLETE is able to straddle the lander and the center-of-mass of the cargo, it avoids imparting tipping moments onto the descent stage (which arrives with empty tanks and therefore is relatively light weight) and thus allows offloading of monolithic cargo elements having mass well in excess of the descent stage mass. Results of a half-scale field test of ATHLETE unloading cargo from a simulated lander are described.

Work described in this paper includes 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.

TABLE OF CONTENTS

1. INTRODUCTION 2
2. THE ATHLETE CONCEPT 2
3. CARGO UNLOADING FROM A HIGH DECK 4
4. HALF-SCALE PROTOTYPE TESTING 7
5. SUMMARY AND CONCLUSIONS 8
6. ACKNOWLEDGEMENTS 9
REFERENCES 9
BIOGRAPHY 9

1

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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 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 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 team studied ways to implement Human Lunar Return (HLR) that had been 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 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 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.

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

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

Soil mechanics studies [6] 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 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 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 [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 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 (Figure 3b). 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.

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

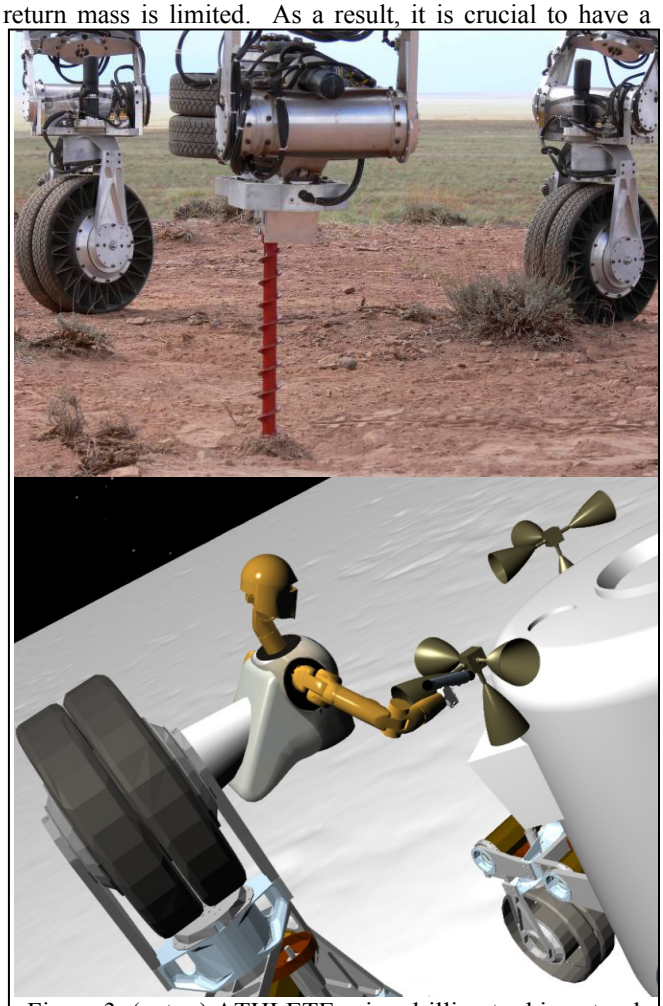

Figure 3: (a, top) ATHLETE using drilling tool in natural terrain, (b, bottom) ATHLETE using Robonaut anthropomorphic robot developed by the Johnson Space Center for tasks requiring human-like dexterity.

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, e.g. to maintain a large organized array of sample containers deployed around the underside of a mobile habitat.

3. CARGO UNLOADING FROM A HIGH DECK

As previously mentioned, the planned Altair lunar lander uses liquid oxygen and liquid hydrogen propulsion for the descent stage. This, together with the fact that (unlike Apollo) the Altair descent stage is 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 that has received the 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. A major purpose of this paper is to address in some detail the difficulty and mass penalty associated with this cargo offloading task. Figure 4 shows a number of terrestrial mobile gantries that are used for offloading and transporting various sorts of bulky and heavy cargo. All of these mobile gantries share common features - they all consist of a number of columns loaded primarily in compression and cables loaded purely in tension to accomplish their task. At the bottom of the compression members are wheel assemblies that impart mobility to the whole apparatus.

In order to estimate the mass of such a mobile gantry as required for lunar operations, it is helpful to analyze a particularly simple and elegant arrangement. In 1992, James Albus and his colleagues at the U.S. National Institute for Standards and Technology proposed the "SPIDER" mobile gantry, shown in Figure 5 [9]. This efficient structurally-deterministic arrangement uses tubular struts purely in compression and cables (purely in tension, of course) attached to winches to achieve very high payload-to-gantry-mass ratios. The term SPIDER is an acronym for "Stewart Platform Independent Drive Environmental Robot".

In order to analyze the mass required for a cargo-offloading mobile gantry, we need to have an estimate for the mass of the structural columns, which clearly (see Fig. 4) will

Figure 4: Examples of Terrestrial Mobile Gantries

constitute a dominant part of the mass of any mobile gantry. The primary failure mode of columns loaded purely in compression is buckling. It is well-known that buckling for such columns occurs long before the yield stress of the native material is reached, so that the compressional columns are much more massive than cables that carry approximately the same loads, since the latter are loaded purely in tension and therefore can approach the limiting strength of the native material.

Euler buckling is one failure mode of such columns, where the column bends in a long arc. Euler buckling occurs when

$$F_{cr} = \frac{2EI\pi^2}{L^2},$$

where F_{cr} is the critical force at which buckling occurs, E is

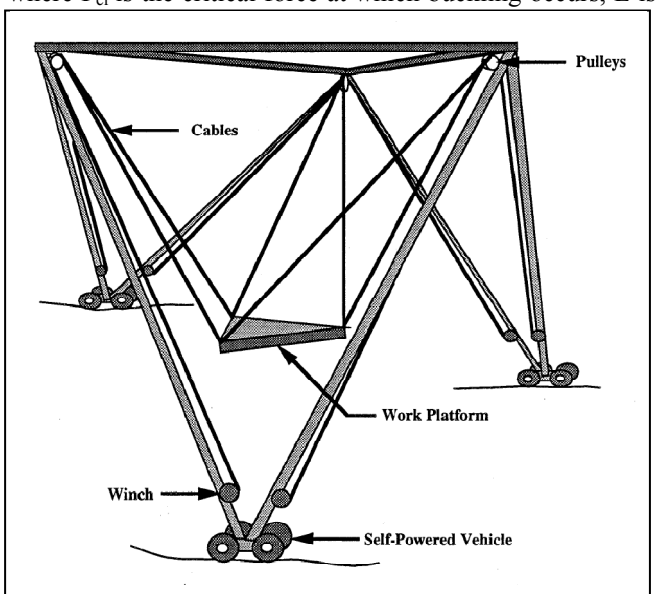

Figure 5: NIST "SPIDER" mobile gantry (1992)

the Young's modulus of the material, I is the geometric moment of inertia of the column cross-section about the long axis, and L is the length of the column. Euler buckling is forestalled by making the moment of inertia I as large as possible. For a thin-walled tube of radius r and wall thickness t, this is accomplished by making r as large as possible. One can keep the total mass of the column bounded by reducing the wall thickness t as r is increased.

However, this process of increasing r and reducing t cannot continue forever. Another buckling process - thin shell buckling sets in, of the sort observed when you stand on the top of an empty aluminum can. Reference [10] gives a good discussion of empirical studies and their relationship to the (somewhat inadequate) theory of this complex process, showing that the observed limiting stress in the column material is proportional to E and to $(r/t)^{-3/2}$. A good fit to the worst-case empirical thin-shell buckling data given in [10] is that

$$\sigma_{obs} = 2E\left(\frac{r}{t}\right)^{-\frac{3}{2}}$$

where σ_{obs} is the observed lower bound on limiting stress at the point where thin-shell buckling can occur. Now $F_{cr} = \sigma_{obs}A$, where $A \approx 2\pi rt$ is the cross-section of the thin-walled cylindrical column. Similarly, $I \approx 2\pi r^3 t$.

A thin-walled cylindrical column has minimum mass when the Euler buckling and the thin-shell buckling conditions are equal - just at the point of failure both buckling modes are imminent. We can equate F_{cr} for both buckling modes and simplify, giving the result

$$r = \left(\left(\frac{F_{cr}}{4\pi E}\right)\left(\frac{\pi^2}{2L^2}\right)^{-5/3}\right)^{3/16}, \text{ and}$$

$$t = r\left(\frac{\pi^2 r^2}{2L^2}\right)^{2/3}.$$

These two equations allow us to estimate the mass of an optimal thin-walled cylindrical member that experiences purely axial loads. First, we calculate the required length L and axial force F_{cr}, including any safety margin. Then, using the topmost of the two equations above, we calculate the necessary radius r of the tube, and then using the lower equation we calculate the thickness t of the thin shell. From the radius and thickness we can calculate the cross-sectional area, and knowing the density we can calculate the mass of the column.

Consider an example. Suppose we need a column 20 meters long that can withstand, including safety margin, 5000 Newtons of axial compression. Then, using Aluminum alloy 7075 (E=70GPa and density ρ=2850 kg/m^3), we compute that r=11.2 cm and t=0.325 mm. The mass of the tube is 13.1 kg.

From the above equations, we see that r is proportional to $F_{cr}^{3/16}$ and to $L^{5/8}$ while t is proportional to $r^{7/3}$ and $L^{-4/3}$, so the mass m of the tube ($2\pi rtL$) is proportional to $F_{cr}^{5/8}$ and to $L^{7/4}$. For Aluminum 7075 the overall constant of proportionality in SI units is 3.37×10^{-4}, so the mass in kg of the minimum-mass tube of length L in meters and ultimate axial force F_{cr} in Newtons is $m(F_{cr},L)=3.37\times10^{-4}\, F_{cr}^{5/8} L^{7/4}$.

So far we have ignored the end-fittings which ensure that the thin shell is uniformly loaded purely in compression. A common way to ensure that the tube is loaded only in compression is to use a "rod-end" at the end-fitting, which is a threaded rod with a ball-and-socket on the end that rotates freely so it can only transmit axial force. The ball has a hole through it so that it can be bolted through a clevis. Reference [11] is a downloadable catalog of high-strength steel aerospace rod ends. Based on the axial force ratings and dimensions in the catalog, together with the density of steel, we can calculate the "specific strength" of these products in terms of Newtons of ultimate load per kilogram. Over a wide range of sizes (from ~30 g to over 1 kg) the observed specific strength of these rod-ends is roughly constant above a worst-case minimum value 3×10^5 N/kg.

An end-fitting connects the tube to the rod-end. It is a custom-machined piece that has a sleeve that fits over the tube for perhaps 1 or 1.5 diameters, and then on the other end is a tapering cone that transmits the load to an axial tapped cylinder into which rod-end stud is inserted. Reference [10] has a good discussion of the importance of ensuring that the load is uniformly distributed around the circumference of the thin cylindrical shell. One way to accomplish this is to bond the tube into the sleeve, making a "liquid shim" that hardens in such a way that the thin tube is protected from radial forces, which would compromise its ability to carry axial loads. Once the bonding agent is dry, the tube is riveted through the sleeve. An appropriate pattern of rivets transmit the load from the sleeve into the tube. Assuming the coefficients of thermal expansion are approximately all the same for the tube, the sleeve, the rivets, and the cured bonding agent, this assembly will satisfactorily deliver the load into the tube in a uniform manner. The shear strength of the bonding agent spreads the load around each rivet so that it is delivered into the tube over a relatively large area. In some cases it is desirable for the tube to be made thicker at the ends where it is riveted into the sleeve. Generally the sleeve is thicker than the tube, and maintains its thickness throughout the conical region that tapers down at typically a 45 degree angle to a thick-walled tapped cylinder that engages the rod-end stud.

We estimate that the sleeve, bonding agent, rivets, and conical region have the same mass as a 5-diameter-long section of the bulk tube. Similarly, we estimate that the tapped cylinder and clevis/bolt together are as massive as the rod-end. We further estimate that the end-fitting, rod-end, and clevis add one diameter of length to each end of the tube. Lastly, we assume a factor of safety of 1.4, meaning that the required axial load is multiplied by 1.4 to compute

F_{cr} as used in the above calculations. The net result of these assumptions is to provide a method for estimating the total mass of each compressive strut in the mobile gantry (or any other application). A numeric least-squares fit for struts from 5 to 25 meters in length over a range of load cases from 75 to 15,000 Newtons gives the approximate formula $m(F,L)= 7.93\times10^{-3} F^{0.622}L^{0.977}$, where m is the mass of the strut in kilograms including Aluminum 7075 tube, end fittings, bonding agent, rivets, steel rod-end, and clevis, F is the design axial load in Newtons (not including safety margin), and L is the length in meters from clevis to clevis. Note that the numerically-optimized exponent for F is almost exactly the same as the theoretical exponent (5/8) for the raw tube, while the exponent for L has dropped from 7/4 to 1. The coefficient in front is about 20 times greater than that for the raw tube. These latter two facts reflect (in agreement with much engineering experience) that, for small struts, the total mass is dominated by the end-fittings and rod-ends. This approximation is accurate to a few percent over most of the range, reaching 10% error only for the very shortest and very longest struts.

We can now return to the exercise of estimating the mass of an offloading system that is capable of handling a cargo at the limit of what the current NASA Constellation architecture is considering (~15 metric tons) from the top deck of the current Altair lunar lander concept (~6 meters high, measured from the surface of the moon). Let us assume that the cargo itself extends another 6 meters above the top of the cargo deck. Let us assume the SPIDER mobile gantry configuration shown in Figure 5, since it is kinematically determinant (e.g. the forces in every element can be calculated from the masses and geometry alone) and all rigid members are loaded only axially.

Since the top of the cargo is assumed to be 12 meters above the lunar surface, we need the bottom of the "work platform" in Figure 5 (that actually attaches to the cargo) to be at a comfortable place within its work volume at that height. That suggests that the triangular top structure of the SPIDER should be some 20 meters or more above the lunar surface. The size of that triangular structure should be such that the mobility elements at the bottom can "open" an aperture to "envelop" the lander. The current 10-meter launch shroud being considered for the Ares-V heavy launch vehicle constrains the Altair and its cargo to fit inside an 8.4 meter cylindrical "dynamic envelope". So let us assume that the Altair and cargo fit within a cylinder 12 meters high and 8.4 meters in diameter. The landing legs will deploy out from this volume at the bottom, but by inspection of Figure 5, the problem with enveloping the cargo by opening the "wings" of the SPIDER mobile gantry is potential collisions at the top of the cargo, not at the bottom of the Altair. When two of the SPIDER "wings" open (e.g. two of the "self-powered vehicles" seen in Figure 5 drive apart), they open a triangular aperture into which the Altair and cargo can pass. What we seek is a minimum-mass gantry that can open sufficiently to accommodate the Altair and cargo and also lift and move 15 tons on the moon.

Armed with the estimation technique derived above for the mass of a compressive strut as a function of load and length, we can formulate an optimization problem based on the geometry of the SPIDER. If the top triangle has edges of length T and the side triangles have diagonal edges of length S, then we can calculate the angle that the wings need to open to to admit the Altair and cargo. If the angle that the wings open is too large, then the load in each of the diagonal struts will increase because they are far from vertical. If S is made larger, the struts can be more vertical and so can be designed to carry smaller loads. Similarly, if the sides of the top triangle T are long, then again the side struts will be less vertical and need to carry higher loads, but if T is too short then it will be hard to envelop the lander.

Since the lunar surface is not smooth and the landing site may not be horizontal, we need to accommodate substantial variations in load from that which would be needed for a flat-and-level floor. We assume that each corner of the top triangle may need to carry two-thirds of the total payload weight (e.g. 10 metric tons in lunar gravity), while the other two corners split the remaining one-third of the weight. Two geometrical facts that are useful here are that the distance from the center of an equilateral triangle with sides of length L to each corner is $L/\sqrt{3}$, and the distance from the center to each side is $L/2\sqrt{3}$. Since the top is an equilateral triangle of side T, the distance from the center to any corner is $T/\sqrt{3}$. If we splay the wings out by having the self-propelled vehicles maneuver on the ground into an equilateral triangle of side G, then the horizontal distance from the center to the side of this triangle is $G/2\sqrt{3}$. That means that the horizontal projection of the opening for the Altair and cargo is a triangle of base G and height $(G/2\sqrt{3})-(T/\sqrt{3})$. In 3-D, that opening is an isosceles triangle with base G and sides S, so knowing its projected dimensions onto the ground allows us to compute the needed lengths. For example, from Pythagoras we compute that the height of the top triangle above the ground to be H, where

$$H = \sqrt{S^2 - \left(\frac{G}{2}\right)^2 - \left(\frac{G}{2\sqrt{3}} - \frac{T}{\sqrt{3}}\right)^2}$$

These considerations allow construction of a spreadsheet to estimate the mass of the struts in a SPIDER with dimensions T and S that is capable of carrying 10 tons of vertical load at the corners of the top triangle, and is capable of admitting the Altair/Cargo by spreading the tips of the wings to a distance G on the ground. Using this spreadsheet we can identify the version having minimum mass. The result of this methodology is that the minimum-mass SPIDER that is able to lift 15 tons and envelop an 8.4 meter wide and 12 meter high Altair/Cargo assembly has diagonal struts 22.4 meters long and top struts 10.9 meters long. Each diagonal strut is estimated to be 48.5 kg, including all end fitting hardware, and is designed for a working load of 9260

Newtons (not including safety factor). The main tube radius is 14.3 cm and the wall thickness is 0.50 mm. The working load translates to a compressive stress of 20.6 MPa, less than 5% of the yield stress of the native material, as expected for column buckling.

Assuming the triangular top frame is designed to the same compressive strength as the vertical members, the mass of each of the top members is 24.0 kg. So the entire compressive structure has a mass of 363 kg, about 2.5% of the design payload in lunar gravity. Other tension members such as cables can operate near their yield stress, as mentioned earlier, and can also be made from high-strength fibers if desired. Thus we can expect the mass of the tension members will be small compared to that of the compressive structure.

We have not addressed the mass of the "self-powered vehicles" seen notionally in Figure 5. Any vehicle that moves cargo on the moon will need something like this, where the mass of the wheels, gears, and motors are subject to the previous discussion about the benefits of being able (or not) of walking out of extreme terrain. So in comparing alternative approaches to unloading and transporting cargo on the moon, all vehicles will need approximately the same fraction of their mass devoted to mobility depending on whether they are capable of walking, or not.

We conclude from this discussion that the heavy compressive structures used to transport cargo in terrestrial mobile gantries such as those seen in Figure 4 can be substituted, in lunar gravity, by structures whose mass is only a few percent of the mass of the payload. Thus it is a relatively small mass penalty to take a vehicle that can transport payload on the moon and make it also able to unload that payload from a high lander deck. Current analysis indicates that the structure mass of ATHLETE is only ~30% greater than a theoretically-optimal configuration such as SPIDER, but the ATHLETE configuration enables walking. Having seen the mass benefits that accrue to walking vehicles by virtue of their lighter wheels and wheel-drive assemblies, it is not surprising that the small mass penalty associated with putting structural members in bending instead of pure compression is overwhelmed by the mass advantages of walking over pure rolling. This is a special case of a more general result that human intuition, developed as it is in one Earth-gravity, can lead to preconceptions about lunar gravity that are simply not valid.

ATHLETE has a number of other advantages over mobile gantries such as SPIDER or those seen in Figure 4, such as the ability to fold up to fit in the launch shroud, to self-unfold and unlatch from the launch configuration once it arrives on the moon. Further, it alleviates some concerns about minimum-gauge handling requirements and the effects of micrometeorites for extremely thin-walled tubes, etc.

4. HALF-SCALE PROTOTYPE TESTING

In 2009, a half-scale ATHLETE vehicle was built, approximately twice the size of the previous prototype (Figure 6). 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 (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.

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 7). 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 8) 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

Figure 6: Half-scale ATHLETE built in 2009, with author for scale.

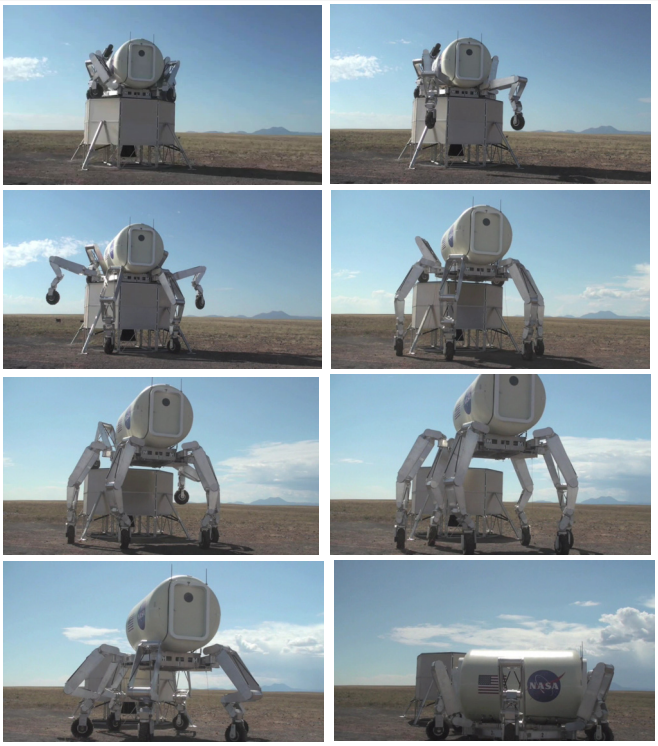

Figure 7: ATHLETE-based cargo/habitat unloading sequence performed at the NASA "Desert Rats" analog field test in Sep 2009. Raster scan starting at upper left shows ATHLETE unloading half-scale payload off a lander mockup by stepping only on the nodes of the simulated tubular space-frame making up the Altair lander structure.

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.

5. 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, 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 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.

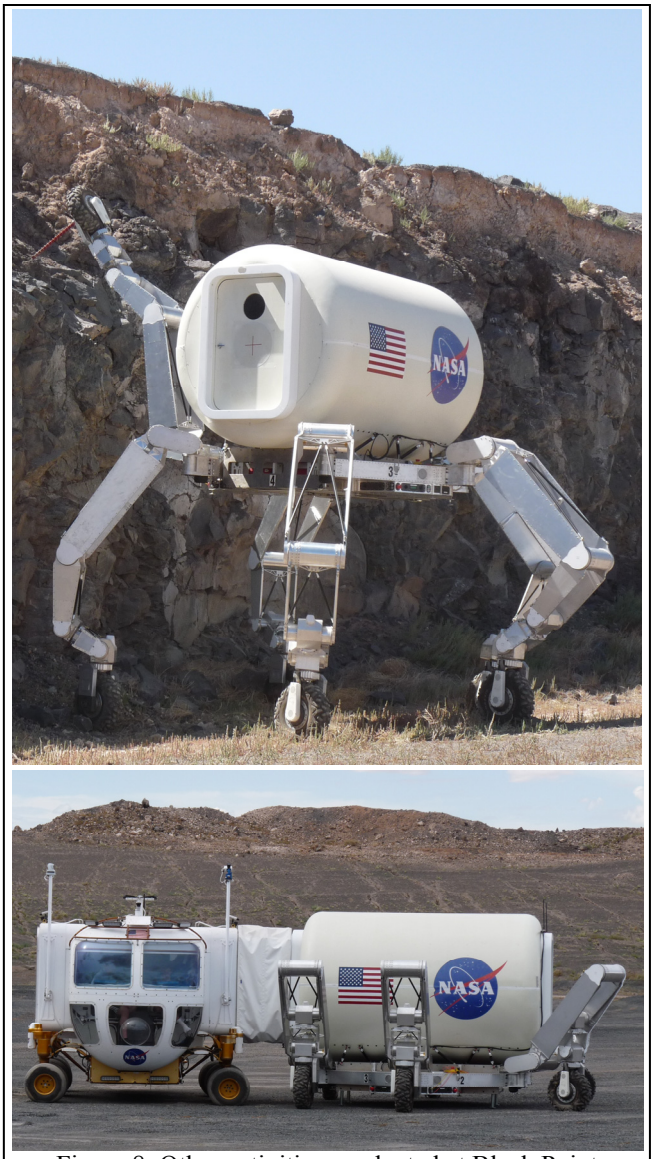

Figure 8: Other activities conducted at Black Point included (top) use of tools, such as drills, grippers, and scoops to take samples of terrrain and manipulate containers, and (bottom) joint experiments with the Lunar Electric Rover, with astronauts directly operating ATHLETE both for mobility and manipulation from within the LER.

The "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 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.

6. 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.