FIELD REPORT

ATHLETE: A Cargo Handling and Manipulation Robot for the Moon

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A robotic vehicle called ATHLETE—the All-Terrain Hex-Limbed, Extra-Terrestrial Explorer—is described, along with initial results of field tests of two prototype vehicles. This vehicle concept is capable of efficient rolling mobility on moderate terrain and walking mobility on extreme terrain. Each limb has a quick-disconnect tool adapter so that it can perform general-purpose handling, assembly, maintenance, and servicing tasks using any or all of the limbs.

1. INTRODUCTION

The Jet Propulsion Laboratory, together with the NASA Johnson Space Center, the NASA Ames Research Center, Stanford University, and the Boeing Company have developed a breadboard of a lunar utility vehicle capable of high mobility on rough and steep lunar terrain. We call this vehicle ATHLETE: the All-Terrain Hex-Limbed Extra-Terrestrial Explorer. The ATHLETE vehicle (Figure 1) concept responded to the call for "Intelligent and Agile Surface Mobility Systems" identified as part of the Lunar and Planetary Surface Operations element of the NASA Technology Maturation Program as part of the effort for a sustainable, affordable, and safe human lunar return. This system was conceived and designed to be capable of moving rapidly and efficiently over rolling terrain at speeds of 10 km/h, more than 100 times faster than the Mars Exploration Rovers (MER), and to be capable of moving over extremely rough or steep terrain beyond the capability of any fielded vehicle. ATHLETE uses wheels on legs (along with possible rappelling on a tether) to accommodate this wide range of terrain. The vehicle uses wheels to roll over smooth terrain, but unlike MER or other fielded space robots, it can use the wheels as feet on the end of legs to achieve unprecedented mobility. One unique advantage of the wheel-on-leg ATHLETE concept is that it combines the high mobility of legged vehicles with the energy efficiency of wheeled vehicles. A second unique advantage of ATHLETE is that each of the limbs can be equipped with a quick-disconnect tool adapter so that tools or general-purpose manipulators can be affixed to the ends of the limbs.

The ATHLETE system addresses a large number of the capabilities that have been identified as important in prior NASA studies, including being highly modular and reusable, providing substantial margins, redundancy, and reconfigurability. The large margins and redundancy enhance human safety because significant failures can occur and still the sys-

(a)

(b)

Figure 1. (a) ATHLETE SDM vehicle climbing natural escarpment. (b) ATHLETE SDM vehicles under test at Dumont Dunes in California.

tem can return to base. The all-terrain mobility performance of ATHLETE makes it possible to preposition logistics from disparate landing sites or to bring in situ resources within useful reach of an outpost.

The breadboard vehicles built in this project were built at approximately half-scale, using similar-performance leg actuators to those planned for use on the moon. The Earth test "Software Development Model" (SDM) vehicles shown in Figure 1 are 850 kg each, 2.75 m diameter, and were built from commercial-grade components that have analogs that can be flight qualified for the lunar environment.

Figure 2. GoFor (1992)—High mobility robot vehicle developed by Brian Wilcox, with wheels-on-legs configuration, able to climb vertical steps of height 70% of the maximum stowed vehicle dimension.

2. PROJECT DESCRIPTION

2.1. Background Information

Previous missions to the moon went to relatively flat terrain where landing would be safe. However, orbiter images show many places on the moon that are mountainous, or that have substantial crater ejecta or other dense hazard fields. The polar regions are very mountainous, largely unknown and unmapped, and yet are attractive sites for future exploration and exploitation. Missions to any of these locales will require a combination of very efficient mobility on relatively flat terrain and very high mobility on challenging terrain. One of the authors (Wilcox) has built previous wheel-on-leg high-mobility robots since 1992 (Figures 2 and 3, among others). These vehicles are able to climb over vertical steps with a height of 50% to 70% of the stowed length of the vehicle, about twice that of the Mars Exploration Rover. The main advantage of the wheel-on-leg configuration for high mobility is that, unlike a conventional vehicle, it does not require thrust from some wheels to generate the traction needed by other wheels to climb obstacles. Instead, each wheel can be lifted by its leg and set on or over an obstacle, like a foot. In very severe terrain, they can just walk like a legged vehicle. But unlike a purely legged vehicle, a wheel-on-leg vehicle is able

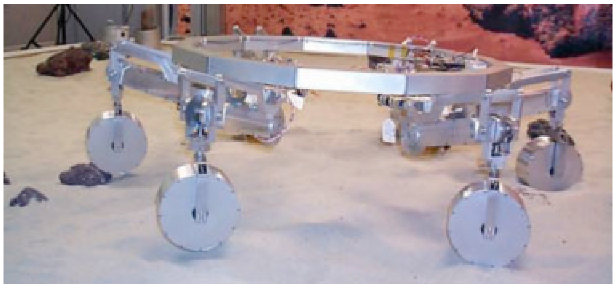

Figure 3. Prior wheel-on-leg vehicle with six wheels in symmetric hexagonal array, able to climb steps 50% of max stowed vehicle dimension.

to roll efficiently and quickly on relatively flat terrain, using much less energy (often a factor of 4 or greater) than a typical walking robot. Thus it combines the advantages of wheels and legs.

The wheel-on-leg assembly is the key subsystem that gives the vehicle high mobility performance and enables manipulation. The kinematics allows the vehicle to plant the wheels in a fixed position and attitude as "feet" when in walking mode, or to roll in any of a wide variety of stances to give the desired ground clearance or weight distribution, or to manipulate payloads and to stow and self-deploy from a very compact form.

Each wheel drive actuator needs a very powerful motor to sustain the 10 km/h speed required for acceptable real-time collaboration with astronauts. Each wheel of the ATHLETE breadboard vehicles is equipped with a ~1.9 horsepower motor, delivering 1755 N peak rim thrust (527 N continuous) at 10 km/h rim speed. Extremely low ground pressure is not required, since the vehicle can "walk" out of situations where one or more wheels begin to sink more than a few tenths of a wheel diameter. For example, in the spring of 2005 the Mars rover "Opportunity" got stuck for many weeks in a soft dune. In that situation, ATHLETE would just walk out. Lunar regolith was reasonably well characterized during past human and robotic missions to the moon—it has been found to be relatively good from a load-bearing point-of-view. So long as the ground pressure of each wheel is limited to about 20–30 kPa, the vehicle should have acceptable sinkage (a few percent of the wheel diameter for cargo-sized vehicles) and acceptable rolling resistance (8–15%) over the vast majority of the lunar surface (e.g., the "2-sigma" situations). These same considerations allow the total rim thrust of the wheels to be matched to the typical cruising conditions, and not to be sized for the absolute worst-case conditions (e.g., the "3-or-4-sigma" design criteria used for previous planetary rovers such as MER, where the rim thrust of each wheel is half the weight of the vehicle). If the "drawbar pull" required to roll the vehicle forward exceeds the combined rim thrust of the wheels, then the vehicle will switch to walking mode. The brakes on each wheel are sized for the worst case thrust loads, however (as they are on the Earth testbed breadboards), so they can be used as feet in the worst-case terrain.

An initial and perhaps obvious question that must be answered is "is ATHLETE too complex or too heavy to be practical for use on the moon?" The low gravity on the moon is a crucial factor in answering this question. Scaling based on the performance of the best flight actuators such as used on MER (1000 Nm peak and 500 Nm continuous output torque per kilogram of actuator), a set of six ATHLETE legs can be configured that are only about 5% of the mobile mass. Because each wheel and wheel-drive assembly only has to work well on "2-sigma" terrain, it can be much smaller and lighter than the wheel and wheel drive that would be needed for "3-or-4-sigma" terrain. Again using the performance of the best MER actuators as a guide, we find that the mass savings on the wheel assemblies is comparable to the mass of the limb structure and actuators, so that, in effect, the limbs add no additional mass beyond that of a mobility system such as used on Sojourner and MER.

Because each leg assembly has to be virtually a complete general-purpose manipulator in order to walk, we have designed a tool interface on each wheel fork so that it can attach and release tools, including general-purpose devices such as grippers. The tool adapter consists of a "square key" akin to that of a socket wrench that rotates with the wheel. A quick-disconnect allows tools to be latched onto the square key, with the latch providing a rigid attachment while the square key provides actuation power. This allows the ATHLETE vehicle to perform almost any assembly, maintenance, or servicing function, if equipped with the right tools. Note that the flight vehicle will be large enough that the tool adapter can reach perhaps 10 m or more above the ground to perform work that human astronauts would find very difficult or dangerous (e.g., on the side of a tall ascent vehicle or crane).

In principle the ATHLETE vehicle can operate in an inverted position, and thus tolerate a situation where it overturned. However, it seems unlikely that any payload would survive such an event, and so it is more important not to overturn in the first place. Like JPL's previous planetary explorers, static stability is continuously monitored to prevent overturning. At higher speeds, dynamic stability will need to be evaluated as well. To date the team has not addressed this issue. On the slow end of the speed range, walking mobility in extreme terrain will be accomplished with a conservative one-leg-at-a-time gait, maintaining static stability on the remaining five-sided polygon of support. Initially, we plan to maintain static stability over the conservative support polygon that is the intersection of all the four-sided polygons that result from a wheel-terrain contact failure of any of the limbs. Thus the gait will be highly irregular, very conservative, and only used in exceptional circumstances, when rolling mobility cannot be used. The transition between wheeled and walking mobility is currently a highly manual process for the operator, and methods to automate that have not yet been addressed.

Each leg and hex-frame side is equipped with multiple cameras so that human operators can control it effectively, and so that autonomous control is possible. On each face of the hex frame is a pair of stereo cameras that performs the same functions as the MER "navcams" and "hazcams" during driving operations. The ATHLETE navcams are used to look for hazards as the vehicle drives, and to provide panoramic stereoscopic HDTV imagery for the operator. Another pair of cameras is positioned on the tool interface to give close-up images of tool-workpiece or wheel-terrain interactions (e.g., sinkage, slippage, squirming, etc.). Budget limitations prevented all the cameras, tool interfaces, and docking adapters from being installed on all positions of the SDM vehicles that have been developed. All cameras in the flight system will be equipped with appropriate lighting (e.g., flashlamps synchronized with the camera shutters) to allow operations to be conducted in total darkness.

Distributed motor control is used on ATHLETE. By distributing the brushless commutation controllers out to each motor, only power and serial data buses need to be routed out the legs. This avoids the very heavy and complex wiring harness containing thousands of wires, of the type used on the Sojourner and MER rovers. The main problem with using centralized motor control is the extreme risk that an intermittent failure in the complex wiring harness late in system integration will be impossible to remedy before launch. If an intermittent fault is discovered late in the integration process, it is essentially infeasible to de-integrate a harness with thousands of wires from the vehicle, re-integrate a spare harness, and adequately validate full functionality in a short time. In the flight version, dual-redundant power and serial data buses will interconnect the flightlike motor controllers, so that no single fault can disable the system. JPL has developed (under the Mars Technology Program) a general-purpose flightlike distributed brushless motor controller that has demonstrated full operation at 110 K, the "winter low temperature" expected on the rim of a lunar polar crater. Each "vision" processor board (one per leg/hex-face) takes input from the four cameras associated with each leg, and performs the "hazcam" function from MER on the stereo pair that looks out from each face. It can also perform stereo vision, feature extraction, or object recognition functions on the "toolcams" associated with the quick-disconnect tool adapter on each wheel yoke.

The hexagonal frame provides the attachment points for the leg assemblies. The batteries (and motor-generators or fuel cells for field operation) are mounted to this frame, as are the docking adaptors for each face of the hexagon. The electronics that controls ATHLETE are also mounted on the inside of the frame. In the flight system, the electronics will be packaged inside multilayer insulation and will use low thermal conductivity (e.g., titanium) mechanical supports that allow the battery/electronic module to stay warm at night or while in shadow with very little heating power.

The docking adapters make the vehicle very flexible and adaptable to novel uses. While a single vehicle can perform simple robotic missions, multiple vehicles can be docked together to perform long-range piloted or robotic exploration missions using appropriate payload modules. Because of the high degree of modularity and redundancy of this approach, it is hard to imagine a failure that would prevent return-to-base. A possible function of the docking adapter is also to mate larger tools to the vehicle, such as a launcher for grappling hooks. Each docking adapter could have a pair of large pin-in-socket electrical connectors so that bus power can flow as soon as mating is achieved. The docking adapters could be strong enough to act as launch restraints for the vehicle, so when they are released the vehicle can just stand up and walk off the lander with no extra deployment hardware or complexity.

The power system for the Earth testbed vehicles consists of three 120 VAC 13 A circuits. In the lab these are supplied by wallplugs and extension cords. In the field, three 2 kW gasoline motor-generators are used. One of the 120 VAC circuits supplies all the commercial computer and related equipment via conventional outlet strips. The other two 120 VAC circuits operate current-limited power supplies that supply 12, 24, and 48 VDC. In particular, the 48 VDC power supplies charge a string of modern high-performance lead-acid batteries to supply power surges as possibly needed by the wheel or leg motors. The lunar flight vehicle is planned to use H_2/O_2 fuel cells and have solar arrays on the legs to regenerate the H_2/O_2 so that a vehicle that runs out of fuel is not permanently lost. Solar arrays on exposed surfaces might also permit laser power beaming into the dark lunar polar craters for vehicle recovery or even normal operations.

The on-board software (SW) development effort started with an implementation based on "lessons learned" from the MER flight software as applied to a multi-processor architecture. The SW development staff for ATHLETE consisted of former MER and Sojourner software developers who implemented both the on-board and ground control software for this project. The MER rovers, like Sojourner before them, are commanded using stereo waypoint designation, a technique invented and matured by one of the authors (Wilcox) in the early 1980s (Wilcox & Gennery, 1987; Wilcox, 1992; Mishkin, 2003). The operator controls the vehicle by visualizing the remote scene in stereo using a 3-D display and maneuvering a cursor in this 3-D space to designate waypoints or activity sites. The vehicle can use the relatively advanced navigation and hazard detection and avoidance techniques of MER to ensure that the activities are completed faithfully and safely. This architecture lends itself to the building of "contingent sequences" of "macro" commands built out of primitives that the vehicle can perform reliably. In this way high levels of autonomy can be built up that the human operator understands and has confidence in. Further, the operator can always drop down to sending low-level commands of the sort "go there and there and then pick that up." Even such low-level commands will allow the vehicle system to be highly productive given the relatively short time delay in Earth-moon communications.

3. APPROACH AND METHODOLOGY

3.1. ATHLETE Mechanical Summary

The ATHLETE vehicle, shown in Figure 4, consists of six identical, six degree of freedom limbs. Attached to the end of each limb is a wheel that can be used for mobility in the form of driving over benign terrain. Alternatively, the wheels can be locked rotationally so that the limbs can be used for walking over rough terrain. The rover body is shaped as a hexagon, giving six flat faces that can be used to dock to similar ATHLETE vehicles, or to other systems such as refueling stations, rappelling winches, etc. The mechanical subsystems are discussed in the following sections.

3.1.1. Limbs

The limbs of the ATHLETE vehicle each possess six degrees of freedom, giving them the ability to walk using the wheels as feet, as well to be used as general purpose manipulators. These limbs can be used to pose the body while driving, walk as a secondary method of mobility, or interact with the vehicle's surroundings as manipulators. Each of the limbs is identical and is composed of the hip yaw, hip pitch,

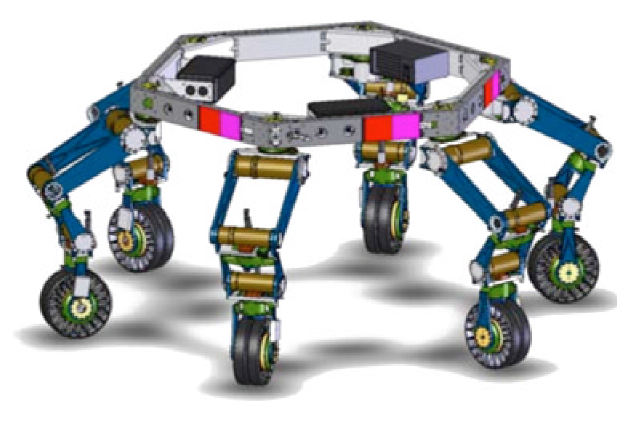

Figure 4. ATHLETE rover shown in nominal driving configuration.

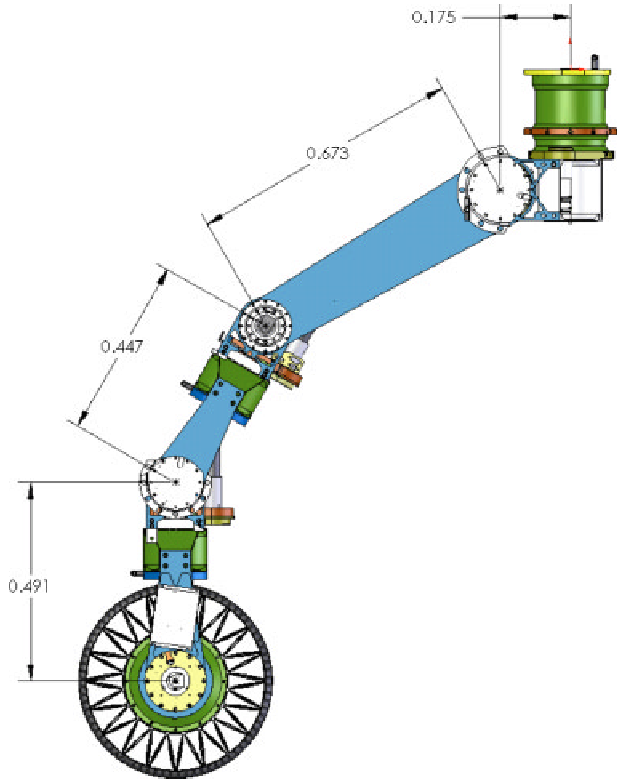

Figure 5. ATHLETE limb.

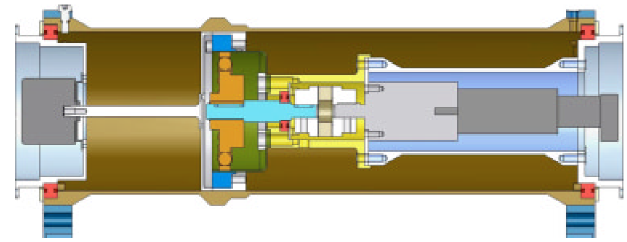

Figure 6. Cross-section of hip pitch actuator.

knee pitch, knee roll, ankle pitch, and ankle roll joints as illustrated in Figure 5 (with dimensions in meters). At the end of each limb is a powered wheel that is used either for driving or for actuating tools during manipulation tasks.

Each joint in the ATHLETE limb is composed of similar design elements that integrate a consistent design philosophy throughout the limbs and reduce the number of unique components. Each joint uses the same Maxon® "EC-max 40" 120 W (mechanical output) brushless dc motor with planetary gearbox as well as a power-off safety brake. This motor is then connected, through a coupling, to a harmonic drive gear to provide the high output torque necessary for each joint. The hip yaw and hip pitch joints both use a harmonic gear reduction providing 3060 Nm of torque before ratcheting. The knee pitch joint uses a harmonic gear providing 1476 Nm of torque. The knee roll, ankle pitch, and ankle roll joints all provide 994 Nm of torque. Figure 6 shows a cross section of the hip pitch actuator as an illustrative example of the joint design.

The two hip joints have a total gear reduction of ~13,000:1. This large gear ratio provides tremendous torque capability in the actuator, but limits the peak output speed to approximately 1 rpm. As the required torque is decreased in the lower joints, so is the actuator total gear reduction. The knee and ankle roll joints have the lowest overall reduction of ~3600:1, giving them peak speeds in excess of 3.5 rpm. Another effect of the large gear reduction is the lack of accurate position knowledge on the output of the gear. The incremental motor encoder is used for control of the mechanism, but this does not measure defections in the structure and gear windup due to unknown external loading. The motor encoder also only provides relative position knowledge and must be calibrated if the main controller loses absolute position knowledge of the joint. In order to account for this, an absolute encoder is integrated directly into the output of each joint. The difference between the absolute encoder output and the relative encoder at the motor shaft gives the "windup" in the gear train, which is observed to be a very accurate (~1%) measure of the actual output torque of the joints. This allows force control, which is crucial to prevent build-up of large internal forces in the multiple closed kinematic chains when the wheels are in rigid contact with the ground. One particular result of this force control is greatly improved climbing performance on uneven but moderately soft natural terrain, so that when the weight is evenly distributed between the six wheels, the maximum sinkage is only about one-third of what it is when there is no force redistribution. Since rolling resistance is roughly proportional to the square of the sinkage, this has a powerful effect on the ability of the vehicle to climb slopes or not to stall the wheel motors.

The limbs of the rover are designed to provide

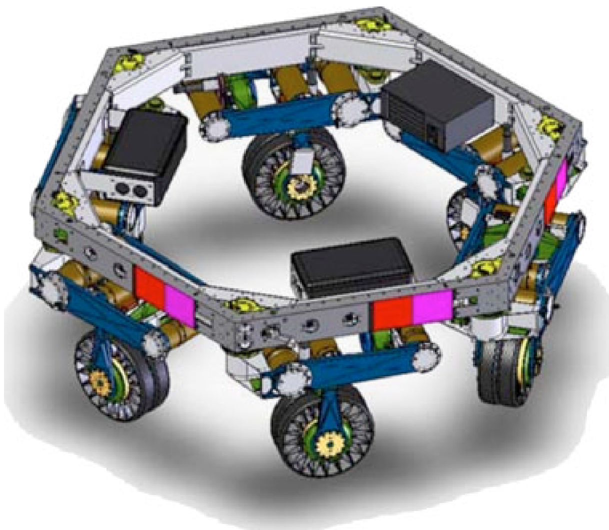

Figure 7. Stowed ATHLETE configuration.

Figure 8. Michelin Tweel.

for compact stowing of the vehicle as shown in Figure 7. The "shins" of the limb can be stowed into the "thigh," allowing the limb to fold back upon itself. This results in a configuration where the vehicle is only slightly wider then the hexagonal frame and only twice as tall as the diameter of the wheel.

3.1.2. Wheels

The primary function of the ATHLETE wheels is for mobility over gentle terrain. The rover is meant to move swiftly, having a top speed of 10 km/h, in order to cooperatively work with humans. The wheel drives of the prototypes provide a peak torque of 423 Nm, which gives more than 1/5 of the vehicle weight as rim thrust at each wheel.

The wheel uses an off-the-shelf servo motor with integrated 36:1 planetary gear reduction. This actuator is coupled to a custom made Michelin® Tweel®. The Tweel is a nonpneumatic tire that provides performance similar to a traditional pneumatic tire with the use of flexible spokes and a sheer band as shown in Figure 8. The Tweels used on the SDMs provide approximately 10 psi of ground pressure, allowing ATHLETE to drive over moderately soft or sandy terrain. For flight, wheels with between 3 and 5 psi would be used as appropriate for the "2-sigma" lunar terrain, as described previously.

The wheels serve multiple functions on the ATHLETE rover. They provide not only the main mode of mobility, but also provide an actuator for tools used during manipulation or cargo handling. Coupled to the wheel is a standard 1/2 in. "socket wrench" square drive that rotates as the wheel is driven.

3.1.3. Structure

The main structure of the vehicle is a hexagonal ring with the hip joints attached at each of the six corners. The structure of the hexagon is welded aluminum c-channel with removable interior close-outs. This structural configuration provides a strong and stiff box section with an accessible interior where the cable harness can reside. The center of the hexagon is left open to provide access for the limbs to manipulate payloads on the top deck by moving the limbs through the center of the hex frame. Attached to two of the interior faces are battery housings. Attached to a third interior face is the main CPU for the vehicle. The flat exterior faces of the frame are used for docking of multiple vehicles together.

3.1.4. Docking

A key feature of the ATHLETE platform is its ability to dock with similar units as shown in Figure 9. This system allows a large array of vehicles to be connected for tasks such as cooperative payload manipulation or the joining of multiple pressurized crew compartment payloads making a mobile habi-

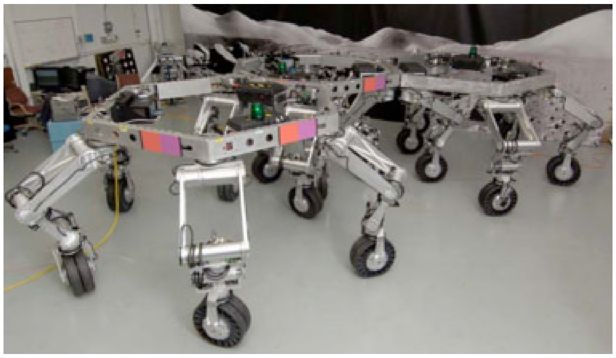

Figure 9. Three ATHLETE vehicles docked together.

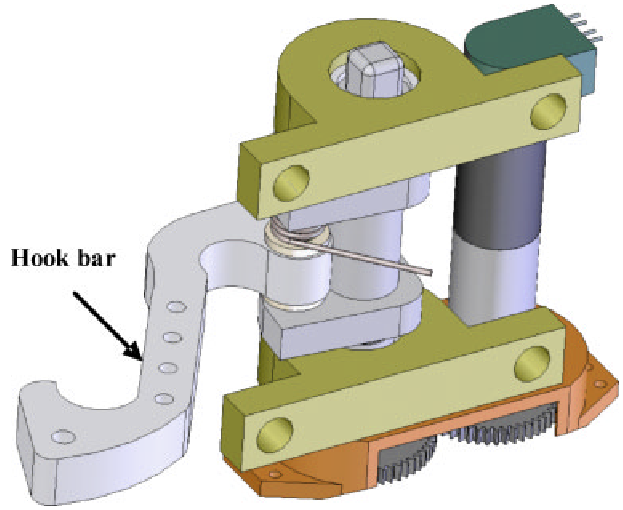

Figure 11. S-hook used for docking.

tat sometimes called a "Habot," which inspired several of the features of ATHLETE (Mankins, 2000). Also, the docking interface can allow mating with a refueling station (e.g., for replenishing H_2 and O_2 used by a fuel cell) or to dock to ancillary equipment such as a "tool belt" or a rappelling winch.

The physical docking between the rovers is accomplished with an over-center mechanism in the face of each ATHLETE vehicle. As two vehicles approach each other, the latching mechanism on one side of the face aligns with the receptacle pin in the opposite side of the face in the mating robot as illustrated in Figure 10.

Once the vehicles are in close proximity, the hooks in both vehicles extend into the opposing receptacles. As the latches engage, they pull the two vehicles together. Mating cups and cones on the docking faces bring the vehicles into precise alignment as the latching mechanism draws the faces together. Due to the over-center design of the latch, torque is only required to drive the cam mechanism during latching and unlatching (Figures 11 and 12). Once the robots are docked, all loads are transferred from the hook directly into the structure, completely isolating the docking motor from the loads.

Due to the symmetry of the faces, any face of a

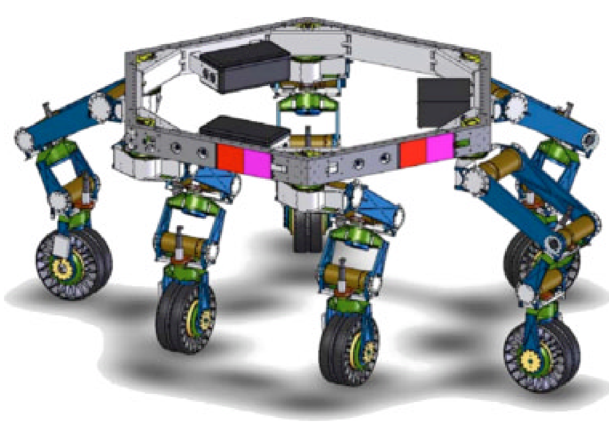

Figure 10. Docking configuration.

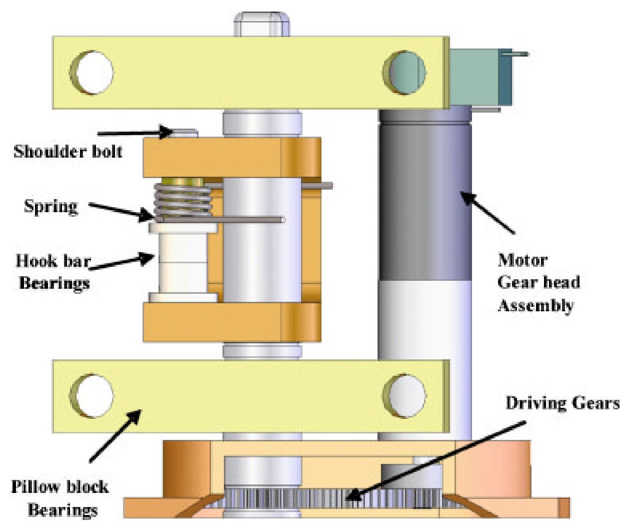

Figure 12. Detail of docking mechanism.

given robot can mate to any face of another robot. The initial alignment of the faces can be done autonomously due to the stereo camera pair and colored target in each robot face. The targets are used to determine the relative positions of the two vehicles, and commands are generated to move them into alignment at a standoff location. A docking sequence is then initiated to bring the robots together. Note that once the vehicles are approximately posed for docking, only "self-motions" of the vehicle are required to achieve precision alignment of the frame elements. That is, no wheel-on-ground motion is required, but purely internal limb motions can maneuver the hex frame in 6-DOF to align it with the mating hex.

3.1.5. ATHLETE SDM Electronics

The ATHLETE Software Development Models are controlled by a commercial central processing units (CPUs), selected based on their functional similarity (at low cost) to a triple-redundant PowerPC 750 Flight Processor that had been identified in the proposal phase as being suitable for the flight version of ATHLETE. These processors operate on a compact PCI bus using a commercial enclosure having a redundant power supply. An RS-422 serial interface is used to communicate with distributed motor controllers.

The distributed cameras are interfaced via firewire (1394) to the computer; with 1360×1024 pixel resolution for the navcams on each face of the hex frame, and 1024×768 resolution for the toolcams at each tool fixture. The servo control boards, as previously mentioned, were selected based on their functional similarity to an extreme-environment motor controller under development at JPL that will allow the motor controllers to be placed on the extremities of ATHLETE with little or no thermal protection (even in the lunar polar craters, where the temperature can get well below 100 K). All motors are brushless, so as to be similar to any flight system. A small custom printed-wiring board was developed for motor support (analog I/O, brake control, etc.).

An 802.11A/G wireless access point/ client allows commands and data to be exchanged with a control station implemented in a bus (used for field operations). Each vehicle has an inertial measurement unit (accelerometers and rate gyros). Power supplies include 480 W 12 V logic supply, 800 W 24 V brake supplies, and multiple 500 W 48 V primary motor bus supplies. The 48 V supplies charge a stack of sealed lead-acid batteries. Batteries' voltage and temperature are continuously monitored.

3.1.6. ATHLETE Software

The ATHLETE software runs on seven identical PowerPC processors. One is used as the main system CPU, handling most aspects of the system, including uplink, telemetry, system control, and mobility. The other six are dedicated to imaging to support real-time machine-vision processing on the six faces/legs while driving. The system is architected so that the vision processors could in the future be used as replacements for a failed central processor, also providing secondary pathways to the motor controllers; this capability is not implemented for the current units.

In order to support a future transition to flight, the software was designed on the model of a real flight system, the Mars Exploration Rovers (MER). This model includes breaking the software into modules, where the modules handle such areas as system initialization, timer services, commands, telemetry, motor control, higher-level mobility, and navigation. Modules are themselves broken into "objects," each of which encapsulates a very limited area of responsibility. Objects are implemented as hierarchical state machines, are loosely coupled, and communicate with each other using asynchronous messages to request services and deliver data (Reeves & Snyder, 2005). The ATHLETE design uses a C++ base class from which all actual objects inherit (an embeddable subset of C++ is used). The base class binds together a state machine and a message queue. Multiple objects can share the same queue, allowing them to run in the same task context. Support software outside any object reads the queue and dispatches messages to the appropriate objects for processing. Samek's implementation of hierarchical state machines is used (Samek, 2002). The majority of the system runs on the main CPU and is composed of nine tasks running 94 objects, plus three utility tasks and one separate communications program without objects. Each of six peripheral CPUs has five tasks running eight objects.

3.1.7. Imaging

Each vehicle has 24 cameras. There are two navcams on each face of the hex and two toolcams just above the wheel on each leg. The cameras are mounted in stereo pairs. Each camera has an approximately 90 deg field of view. The navcams are positioned to support driving. The toolcams are positioned to support tool and manipulation activities as well as for looking under the vehicle. Images from all the cameras are available both for human viewing and for autonomous use.

Ground commands can request that images be acquired from any camera individually or simultaneously from any stereo pair. The images are sent to the ground in the telemetry stream. In addition to the commands that request images on demand, there are commands to start and stop video streaming. A video stream is an ongoing series of images at a specified rate meant for near-real-time human viewing. The stream is throttled automatically to match the downlink telemetry bandwidth.

On MER the single command to acquire images was very complex, with many arguments to match the many acquisition and processing options that were available. While workable, having to supply every argument all of the time proved to be quite clumsy. On ATHLETE the commands are split out into two sets, one simple and one more complex. The simple one includes only those arguments that change routinely; defaults are used for the rest. The required arguments include the camera or cameras from which images are to be taken, and whether the images should be monochrome, color, or the underlying raw Bayer pattern from the CCD. The extended arguments include specifications for subframing, spatial downsampling, pixel size, and compression. The ICER and LOCO compressors from MER were used (Litwin & Maki, 2005). The simple command forms are used almost all the time.

The cameras are calibrated using the same models that were used on MER (Litwin & Maki, 2005). These models provide a mapping between the vehicle's shared 3D coordinate system and 2D image coordinates. All images are delivered with models attached so that the recipient has all the information needed to interpret the geometry of the scene. In the case of the toolcams, which are mounted on legs that move with respect to the vehicle coordinate system, which is rigidly attached to the hex frame, the models are transformed to correspond to the instantaneous camera pose.

3.1.8. Visual Docking

In order to dock two ATHLETE vehicles together, it is necessary to align a face of one vehicle with that of another. The alignment tolerance is approximately 1 cm between corresponding points on the faces. Manually commanding the vehicle pose for docking is tedious and error-prone. To support automating the process a vision-based method has been adopted. While one vehicle remains stationary, a second vehicle visually tracks the position of the first while approaching it. Both the approach trajectory and the final body alignment are guided by vision data.

Based on earlier work (Volpe, Litwin & Matthies, 1995), a two-color target was designed and placed on each face of the vehicle; see Figure 13(a). Images are acquired using stereo navcams on the moving vehicle. They are analyzed in HSV color space to locate the target in each view. Stereo triangulation is used to determine the 3D location of each color block's center of mass. The vector direction to the target and partial target orientation are computed. This process is repeated at several Hz throughout the approach process.

The current implementation suffers from two deficiencies. Only two rotational degrees of freedom for the target are determined. Also, tracking fails once the vehicles are so close that part of the color target is outside the field of view of either camera; this occurs just under 0.5 m of separation. Future refinements to the target design are planned to address these shortcomings. At present the visual tracking data are sent to the ground, where operators use the information to construct the appropriate commands for docking. Ground software assists in the process. In the future a fully autonomous onboard system will be developed to close the loop.

3.1.9. Visual Odometry

The first step in determining the motion of a wheeled robot is to use dead reckoning based on wheel odometry. The accuracy of this approach can be seriously degraded by wheel slippage. To augment dead reckoning other sensor data can be used. An inertial measurement unit (IMU) adds information about orientation but does not help with translation. Vision-based analysis of the scenery can add information on both translation and rotation.

Visual-odometry software based on prior JPL

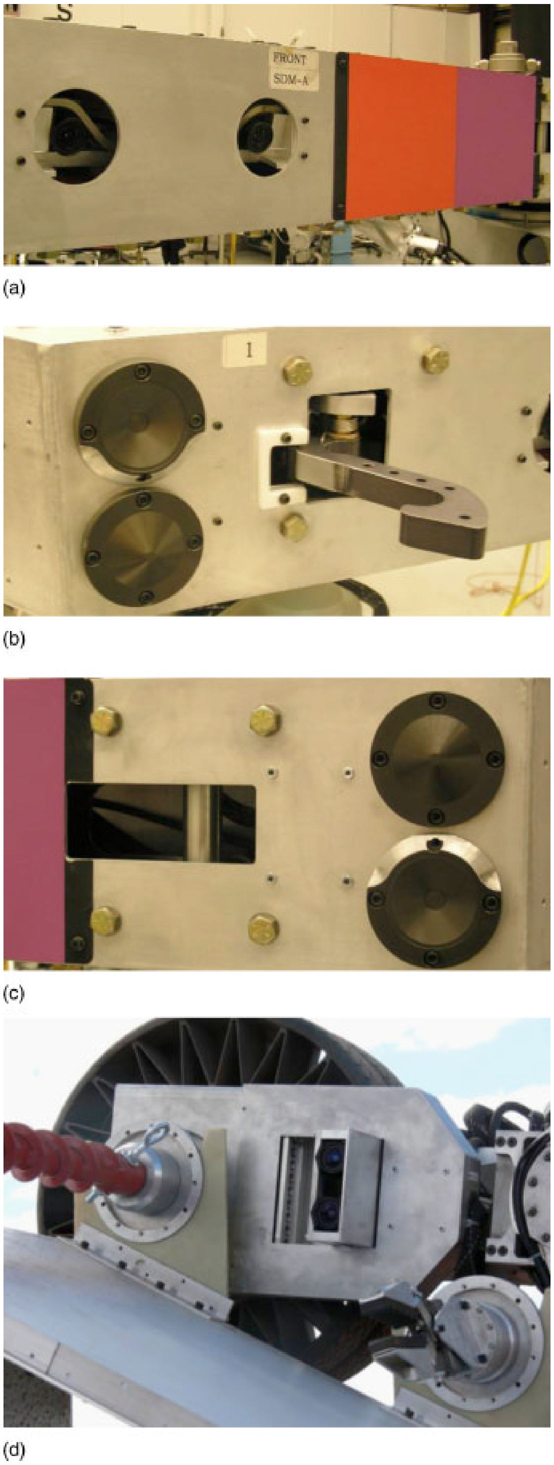

Figure 13. (top) Stereo HDTV cameras and docking target. (b) docking fixture, (c) docking recepticle, and (d) (bottom) extracting tool (drill) from toolbelt, showing stereo HDTV toolcams.

work has recently been integrated into the system. Testing has only just begun, and no performance data are yet available. But successes on MER suggest we can expect good results (Cheng, Maimone & Matthies, 2005).

3.1.10. Future Plans for Visual Analysis

Over the balance of the program the following additional capabilities are planned:

- Stereo range maps. Dense 3D maps of the surrounding terrain will be produced. This data will be used for the following two capabilities.
- Hazard detection. The terrain maps will be analyzed while driving to identify potential hazards, allowing the vehicle to stop or drive around the obstructions.
- Footfall analysis. The terrain around the vehicle will be analyzed while walking to find suitable locations for placing the feet.
- Gesture recognition. Astronauts working alongside the vehicle will be able to make physical gestures with their bodies to issue commands.

3.1.11. Motion Control Software

The current command set for initiating vehicle motion consists of four different classes of commands: joint-space, Cartesian motion of one or more legs, Cartesian motion of the body keeping the wheels planted, and driving maneuvers. There was considerable design inheritance from the MER motor control, driving, and instrument deployment device control flight software.

Joint-space commanding allows an arbitrary set of joints to be run to prescribed angles—either relative to current joint angles or to absolute angles. Motion is coordinated in that all specified motors are started simultaneously, with their peak velocities scaled so that goal angles are nominally reached simultaneously. A fault on any motor in the set halts all motors in the set. It is interesting to note that it would be rare for a single failed motor to disable the vehicle because of the large degree of redundancy in the system design. In the unlikely event that an actuator fails in a pose that disables the vehicle, adjacent limbs can make use of tools to amputate the failed limb.

Cartesian commands for moving the legs specify a goal position and orientation for the wheel fork of each leg (currently treated as a 6-DOF manipulator) to be moved. Position and orientation are linearly interpolated at intermediate via points, to give straight-line translation and smooth re-orientation. Motion from one via point to the next is done in joint-space, and advancement to the next goal via point is done when all joints angles are sufficiently close to the current goal. The tolerances are set to allow advancement while the legs are still moving, to avoid stopping at each intermediate position (which would cause jerky motion). If multiple legs are moved in the same command, their motions are coordinated to start and nominally end at the same time (even if one leg is to physically translate more than another). The entire trajectory is precomputed before any motion is done, and motion is not started if any part of the trajectory is unreachable.

Cartesian commands for the body allow a new body position and orientation to be specified. Intermediate via points are computed to allow the body to translate in a straight line and change orientation smoothly. The positions and orientations of each wheel fork are computed at these via points, to remain fixed in the global frame. One application would be doing fine body repositioning when docking two vehicles on rough terrain.

Currently, driving commands are implemented as standard 2D Ackerman driving primitives for all-wheel steered vehicles. This means the vehicle can drive along arbitrary circular arcs—about any pivot point. Ankle roll actuators are used for steering, and wheel speeds are scaled according to the turn radius at each wheel (wheels on the outside of a turn must spin faster than those on the inside of a turn). Straight-line driving and turn-in-place are special cases of the arbitrary circular arc primitive.

Future work consists of integrating new sensors (absolute encoders on the output of each leg joint, and force-torque sensors in each ankle) into control loops—allowing forces to be balanced at each wheel while driving and walking. Additionally, machine vision terrain assessment and predictive hazard avoidance will also be integrated.

4. SUMMARY AND CONCLUSIONS

This paper describes the ATHLETE vehicle concept and the details of two fully operational (and a third partly operational) Software Development Models. Testing in the Mojave Desert of California and the terrain near Meteor Crater in northern Arizona confirms the power-efficient rolling mobility envisioned as part of the concept, especially when the contact forces are sensed and the pose of the vehicle adjusted to equalize the weight on each wheel. A quick-disconnect tool adapter has been developed for the limbs that allows the wheel motor to power any tool. Several tools have been developed, including a drill and a gripper. These tools have been extracted automatically from a "tool belt" and used for tasks such as drilling holes in the terrain, picking up moderate-sized payloads, unspooling umbilicals, etc.

ATHLETE is designed with smaller wheels and wheel drive actuators than would be used in a conventional vehicle, since they only need to successfully roll over "2-sigma" terrain, while walking mobility is used on more extreme terrain. The mass savings of these small wheel assemblies largely offsets the mass of the limbs and their actuators. Because of the low gravity on the moon, it appears that the mass of ATHLETE limbs can be as little as 5% of the gross mass of a vehicle. One attractive implication of this is that landers could be made mobile by using ATHLETE limbs to stabilize them during landing while using airbags or crushable material under the launch adapter ring to absorb the primary impact energy. If landers are mobile, then there may be no reason to have separation interfaces to their payloads, because those payloads can be moved by the ATHLETE lander mobility system to wherever those payloads are needed. The mass savings by eliminating these separation interfaces may be greater than the mass increase for an ATHLETE-based landing system as compared to conventional landing legs such as those use by Apollo. Thus an ATHLETE-based lander, capable of power-efficient rolling mobility on moderate terrain, walking mobility on extreme terrain, and general-purpose manipulation and tool use, might actually be less massive than the straightforward alternative having none of these benefits. (Bluethman et al., 2004; Bretl, Lall, Latombe & Rock, 2004; Bretl, Latombe & Rock, 2003; Bretl, Miller, Rock & Latombe, 2003; Bretl, Rock & Latombe, 2003; Bretl, Rock, Latombe, Kennedy & Aghazarian, 2004; Hickey, Kennedy & Ganino, 2000; Kennedy et al., 2001; Kennedy, Aghazarian, Garrett, Okon & Robinson, 2004; Kennedy, Garrett & Okon, 2006; Kennedy & Leger, 2004; Kortenkamp, Hober & Bonasso, 1996; Litwin & Maki, 2005; Nickles & Huber, 2001; Sreenivasan & Wilcox, 1994).

Figures 13(a)–13(d) show some details of many elements of the ATHLETE system developed as part of this project.

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