Rough and Steep Terrain Lunar Surface Mobility

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Abstract: In the summer of 2004, the NASA Exploration Systems Mission Directorate conducted an open call for projects relevant to human and robotic exploration of the Earth-Moon and Mars systems. A project entitled "Rough and Steep Terrain Lunar Surface Mobility" was submitted by JPL and accepted by NASA. The principal investigator of this project describes the robotic vehicle being developed for this effort, which includes six "wheels-on-legs" so that it can roll efficiently on relatively smooth terrain but walk (using locked wheels as footpads) when "the going gets rough".

Introduction: Previous missions to the moon went to mostly flat terrain where landing would be safe. However, orbiter images show many places on the moon that are very mountainous, or that have crater ejecta or other dense hazard fields. The polar regions are largely unknown and unmapped, and yet are attractive sites for future exploration and exploitation due to the possible presence of frozen volatiles, especially water ice. Missions to any of these locales will require a combination of very efficient mobility on relatively flat terrain and very high mobility on extreme terrain. A challenge identified in the Lunar and Planetary Surface Operations element of the Human & Robotic Technology (H&RT) Formulation Plan and the NASA Intramural Call for Proposals (ICP) is to develop "Intelligent and Agile Surface Mobility Systems, both piloted and unpiloted." The project described in this paper addresses that challenge with ATHLETE (All-Terrain Hex-Leg Extra-Terrestrial Explorer). This PI has built wheel-on-leg high-mobility robots since 1992 (Figures 1 and 2, among others)[1]. 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 (MER). The mobility performance metrics of the proposed ATHLETE design over the current State-of-the-Art were given previously in Table 1. 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 to roll efficiently and quickly on relatively flat terrain, using much less energy (~4X) than a typical walking robot. Thus it combines the advantages of wheels and legs.

Figure 1: GoFor (1992) High mobility robot vehicle developed by this PI with wheels-on-legs configuration, able to climb vertical steps of height 70% of the maximum stowed vehicle dimension.

The terrestrial ATHLETE vehicle (Figure 3) testbed is being built with commercial-grade actuators and electronics but will be functionally equivalent and use much the same interfaces and software as the lunar flight system. This terrestrial vehicle will be half-scale compared to the lunar flight system (2.75 m diameter instead of 4.5 m diameter). The structural mass of the half-scale vehicle will be about half that of the lunar vehicle, since each link will need about the same cross-section to handle the torque of the same actuators, but each will only be half as long. By virtue of this scaling, the 500 kg terrestrial vehicle will deliver the same effective force-to-weight ratio as the flight system will have on the moon at 1500 kg (including 750 kg payload plus fuel supply sufficient for several days).

The current Technology Readiness Level (TRL) of this technology is 4 (component and/or breadboard validated in a laboratory environment) as demonstrated by the Lunar Hexabot shown in Figure 2. This vehicle has approximately the same configuration and control architecture as the proposed ATHLETE vehicle. All 18 of the actuators on the Lunar Hexabot are controlled and fully coordinated by a distributed control architecture similar to that planned for ATHLETE. At the end of this project the TRL will be 6 (system/subsystem model or prototype demonstration in a relevant environment) since ample field-testing in natural terrain will have validated the all-terrain performance of the ATHLETE vehicle, and flight-like actuators and robotic electronics (e.g. motion control and vision I/O) will have been environmentally qualified in chamber testing to survive approximately 10 years in the lunar equatorial or polar environment.

The ATHLETE vehicle system engineering parameters are given in Table 1. The major subsystems are:

1. Six Wheel-on-Leg assemblies which include distributed sensing, computation, and control electronics,
2. A hexagonal frame,

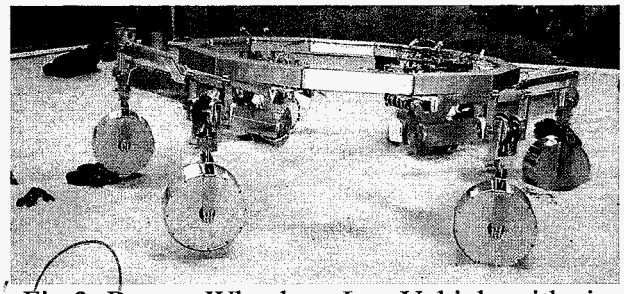

Fig 3: Recent Wheel-on-Leg Vehicle with six wheels in symmetric hexagonal array, able to climb steps 50% of max stowed vehicle dimension.

3. Docking adapters on each side of the hexagon, and
4. A power generation and storage system.

Each of these subsystems will now be briefly described.

1. The Wheel-on-Leg assembly is the key subsystem that gives the vehicle high mobility performance and flexibility. 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, operate upside-down, self-right, and stow and self-deploy from a very compact form.

Each wheel drive actuator needs a very powerful motor to sustain the 10-km/hr speed needed acceptable collaboration with astronauts. A rule-of-thumb for wheeled rovers is that the total electrical bus power

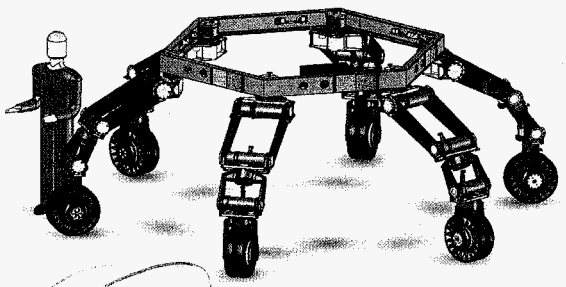

Figure 3: Rendering of ATHLETE Software Development Model being built in 2005

	Earth Testbed	Lunar Flight Vehicle
Mass (kg)	500	1500 (inc. 750 kg payload)
Power (Watts, average)	5000	5000
Size (hexagon diagonal, m)	2.75	4.5
Continuous Speed (m/s [km/hr])	2.78 [10 km/hr]	2.78 [10 km/hr]
Power Source	Fuel Cell/batteries or motor-generator	Regen/refuelable Fuel Cell/Li-ion Bat/Solar Arry
Number of wheels-on-legs	6	6
Max total wheel thrust to vehicle local weight ratio	1.2 to 1	2.4 to 1
Cruise total wheel thrust to vehicle local weight ratio	0.4 to 1	0.8 to 1
Max total leg lift to vehicle local weight ratio	3 to 1 (in worst case pose)	4 to 1 (in worst case pose)
Ground Pressure @ 1 radian wheel sinkage (PSI [kPa])	2.6 [18.1]	1.3 [9.1]
Cameras per leg	4 (hazcam stereo pair, wheel-tool-soil stereo pair, night driving lights)	4 (hazcam stereo pair, wheel-tool-soil stereo pair, night driving lights)
Docking adapter (each face)	mech. dock+ power	mech. dock+ power
Dockable Grappling Winch	Winch w/ 50 m cable, releasable grappling hook, launch mechanism az/alt pointing, stereo cameras, vision and motor controllers	Winch w/ 150 m cable, releasable grappling hook, launch mechanism az/alt pointing, stereo cameras, vision and motor controllers

Table 1: Summary of System Engineering Characteristics of ATHLETE Lunar Vehicle.

required for the vehicle will be the cruising speed multiplied by an effective drawbar pull force (that accounts for all losses) equal to half the vehicle weight in the local gravity. For the 500 kg Earth testbed at 10 km/h, this is over 1 horsepower per wheel. A flight wheel actuator will be developed and qualified for a nominal 10-year life on the moon that outputs the same mechanical power at the same cruise speed with wheels twice as large.

The ground pressure of the Earth testbed will be larger than the lunar flight vehicle. The roughly double-scale lunar vehicle will have the same size wheels as the Earth testbed, and three times the mass, but will operate in $1/6^{th}$ gravity. The Earth testbed has a ground pressure similar to most dune buggies, while the lunar flight vehicle has exceptionally low ground pressure (comparable to the Mars Exploration Rover) for high performance in the softest of terrain.

Each leg assembly has to be virtually a complete general-purpose manipulator in order to walk effectively. The kinematics of each leg is yaw-pitch-pitch-roll-pitch-roll, which is the same as the venerable PUMA manipulator. We will put a tool interface on each wheel fork so that it can perform general-purpose manipulation functions. This tool interface includes a pair of cameras that provide close-up stereo imagery of the tool worksite. It is envisioned

that a "tool holster" can provide many sorts of tools ranging from rotating tools for helical fasteners or drilling, to clamping tools such as pliers, to general purpose manipulators. More complex tools will use a wireless command interface to the ATHLETE computer so that any sort of custom motorized tool can perform almost any conceivable assembly, maintenance, or servicing function. Note that the flight vehicle will be large enough that the tool can reach about 6 meters (19 feet) above the ground to perform work that human astronauts would find very difficult or dangerous.

Each face of the hexagonal frame will be equipped with stereo cameras so that human operators can control the vehicle effectively, and so that autonomous control is possible. These stereo cameras combine the functions of the MER "hazcams" and "navcams" during driving operations. The hazcams are used to look for hazards in front of the wheels, while the navcams are used for long-range planning. These cameras will be high enough off the ground to function as navcams, and will be high resolution enough to function as hazcams. All camera systems will be equipped with suitable lighting (e.g. flashlamps synchronized with the electronically shuttered cameras) to allow operations in total darkness.

2. The hexagonal frame provides the attachment points for the leg assemblies. For the flight system, the fuel cells and batteries will be mounted to this frame, as will the docking adaptors on each face of the hexagon. The electronics that controls each leg will be mounted with the associated batteries on the inside of the corresponding frame element using multilayer insulation and low thermal conductivity titanium supports that allow the battery/electronic module to stay warm at night or while in shadow with very little heating power (about 1 W).

3. 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 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. Each docking adapter will 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 will 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.

4. The power system consists of a fuel cell assembly and battery assembly with associated battery charging and power management circuits. For the Earth testbed, we plan to use a commercial methanol/air fuel cell if that technology becomes sufficiently mature, or a motor-generator power source (as used on the Software Development Model), while on the moon presumably NASA will advance Apollo-era H_2/O_2 fuel cells into a standardized architectural component. The lunar vehicle is planned to 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. The solar arrays would also permit laser power beaming into the dark lunar polar craters for vehicle recovery or even normal operations.

The overall objective of this four-year project is:

1. To develop and demonstrate the ATHLETE vehicle moving in a relevant environment at least 10 km/hr over moderate terrain and achieving ultra-high-mobility on extreme terrain.

2. Flight-qualify all technology components that are needed to ensure that aerospace industry will be able to produce this vehicle

for NASA with affordable cost and schedule to support Human Lunar Return (HLR).

Specifically, the Phase I (Year 1) objectives and specific aims are:

1. Demonstrate a Software Development Model of a wheel-on-leg vehicle (shown in Fig. 3) maneuvering in smooth terrain and performing docking.

2. Conduct a flight-like system engineering and subsystem/component Preliminary Design Review.

The Phase II -Year 1 objectives and specific aims are:

1. Conduct a system engineering and subsystem/component Critical Design Review.

2. Demonstrate and quantify performance of critical component technologies identified in Phase I.

The Phase II -Year 2 objectives and specific aims are:

1. Build complete approximately half-scale Earth-test vehicle using commercial versions of the flight actuators and electronics.

2. Initiate flight qualification of all technology components needed for aerospace industrial contractor to produce flight ATHLETE vehicles for NASA.

The Phase II -Year 3 objectives and specific aims are:

1. Perform functional testing of vehicle in relevant environment and document performance against metrics (e.g those given in Table 1).

2. Flight qualify all robotics technology components (e.g. actuators and custom vision components).

3. Perform a manufacturing analysis and transfer technology to industrial partner so that vehicles are available to NASA at affordable cost and schedule to support HLR (including robotic precursor and logistics prepositioning missions).

Approach and Methodology: Principal Investigator Brian Wilcox leads the overall Project, and Project Manager Curtis Tucker manages all day-to-day operations to ensure that all elements maintain schedule and budget. Co-Investigator Mark Henley, an experienced flight system manager at Boeing, leads the Manufacturing Analysis work element to ensure that the final product is affordable for NASA, reporting regularly to the PI and PM so that any needed changes are implemented with minimum impact.

JPL is responsible to ensure that the system and subsystem designs meet the objectives, perform all system engineering functions as well as all detailed design and analysis functions needed to create the Software Development Model, the Earth Testbed Vehicle, and procurement of commercial actuators and their flight equivalents, including qualification.

The effectiveness of the computing and software architecture and implementation is key to the success of this project. One key component of electronics architecture is a distributed motor controller module that has been developed for the Mars Science Laboratory. This module has undergone thermal testing to -120C, and will be extended to both -180C and +125C under this project. The same technology used to develop this module will be used to develop a flight vision processor, similar to one recently developed for a military sponsor. The vision processor developed by this team for the military performs stereo correlation at 10 frames/second, more than two orders of magnitude faster than is done on the MER rovers.

Dual-redundant power and serial data buses interconnect the flight-like motor controllers, so that no single fault can disable the system. Each leg will have such redundant buses, commanded by a single vision processor board per leg. The vision processor board will have inputs for the 4 cameras on each leg, and will perform the "hazcam" function from MER on the stereo

pair on the corresponding side of the hex frame. The vision processor associated with each leg will perform both vision and general-purpose computing and communicate with the vision processors on the other legs via redundant, high-speed buses.

The on-board software is based on the MER flight software as ported to the distributed vision processor architecture, with ATHLETE team members who played a major role in the development in the MER flight software. Similarly, key implementerx of the ground control software for MER are developing the ATHLETE ground control system. ATHLETE, like MER and Sojourner before it, is commanded using stereo waypoint designation, a technique invented and matured by this PI in the early 1980s [2-4]. 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 uses advanced navigation and hazard detection and avoidance techniques 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.

Co-Investigator Jean-Claude Latombe of Stanford University is leading the effort to develop algorithms for footfall placement of the wheels when walking on soft, steep slopes or on terrain that is too rugged for rolling mobility [5-9].

Co-Investigator Rob Ambrose of the Johnson Space Center leading the effort to develop an astronaut interface that will allow a suited astronaut to issue voice and gesture commands to the vehicle, translating those commands into the same command strings that are generated by the ground control station, based on his team's extensive experience with human-astronaut interactions [10-12].

Co-Investigator Illah Nourbakhsh of NASA ARC (on leave from Carnegie Mellon University) is leading an effort to develop a real-time retasking executive to sit on top of the current MER executive.

The team has embarked on an intensive activity to assure that the ATHLETE will become an effective basic building block for all construction, transportation and other surface activities and will enable easy infusion of this technology to other Exploration systems.

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control the GoFor vehicle (Fig. 2) developed by Wilcox in 1992. Dr. Sreenivasan is now an Associate Professor of Mechanical Engineering at UT Austin.)

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