Field Experiments in Mobility and Navigation with a Lunar Rover Prototype

David Wettergreen[1], Dominic Jonak, David Kohanbash, Scott Moreland, Spencer Spiker, and James Teza

Abstract Scarab is a prototype rover for lunar missions to survey resources, particularly water ice, in polar craters. It is designed as a prospector that would use a deep coring drill and apply soil analysis instruments. Its chassis can transform to stabilize its drill in contact with the ground and can also adjust posture to ascend and descent steep slopes. Scarab has undergone field testing at lunar analogue sites in Washington and Hawaii in an effort to quantify and validate its mobility and navigation capabilities. We report on results of experiments in slope ascent and descent and in autonomous kilometer-distance navigation in darkness.

Introduction

Figure 1. Scarab lunar rover prototype on unconsolidated sandy soil in eastern Washington

To discover and measure the resources of the moon, robotic systems will have to survive extremes from blazing sunlight to frigid darkness as well as dust, vacuum, and isolation. Scarab is a prospecting rover developed to perform the necessary science operations to locate volatiles and validate *in situ* resource utilization methods. [Sanders09] (Fig. 1) It is a terrestrial concept vehicle designed to deploy a deep coring drill and to transport soil analysis instruments. The vehicle design employs a passive kinematic suspension with active posture adjustability. Its chassis can lower to stabilize a coring drill in contact with the ground and can also adjust to control roll, meaning

[1] Carnegie Mellon University, 5000 Forbes Avenue. Pittsburgh, PA 15213, dsw@ri.cmu.edu

rotation about its longitudinal axis, by independently adjusting its side-frames. This allows it to drive cross-slope and turn switchbacks to better ascend and descend unconsolidated soil.

Scarab is intended to operate on and within lunar craters, particularly in polar regions. Because the interior slopes and crater floor are sometimes in shadow, or in some cases in permanent darkness, active sensing methods are needed for terrain modeling and autonomous navigation. Scarab employs laser range scanners with autonomous navigation algorithms to build models of the surrounding terrain to detect obstacles and then determine efficient and safe paths.

In this paper we review results from field experiments at Moses Lake Dunes, Washington and Mauna Kea, Hawaii to measure and verify the prototype rover's ability to meet the demands of a lunar polar crater prospecting mission.

Rover Configuration

Scarab was conceived as a work machine with a serialized mission: drive, charge batteries, drill, charge again, analyze soil samples, charge and repeat. The number of repetitions might be 25, leading to 25 kilometers of traverse, 25 cores, and 25 sites surveyed. For some craters, 100 repetitions might be more desirable to characterize the environment and resources.

There are many factors effecting the rover configuration but the drill mechanism and its operation dominate. The requirement to transport and stabilize a deep coring drill literally became central to the design while requirements for ascent and descent in cratered terrain shaped many aspects and fine details.

Drilling requires a stiff platform into which thrust loads, torques and vibrations are transmitted and hole alignment is maintained. Placement of the drill in line with the vehicle's center-of-mass maximizes the mass that can be applied in down force. (Fig. 2) Drilling operations receive three benefits of this feature; first, lowering the chassis allows the full stroke of the drill to be used in the soil resulting in mass savings overall. Secondly, the rover can lean and therefore re-stabilize and place the rover center-of-mass over the drill core. Lastly, under low gravity conditions, the drill torques are counteracted by the increased leverage arm created by spreading the rover wheelbase.

The rationale for the vehicle weight and size is based on the 1 m long, 3 cm diameter drill that is likely to be employed in a lunar mission. Not only does the rover have to support the drill but also it must provide sufficient weight against which the drill can react its downward thrust and torque about the bit. Drill thrusts are expected to reach 250 N and 50 Nm torque. The system weight on lunar surface must react drilling 250 N downforce and maintain 150 N on wheels for stability against uplift and spin, therefore total weight on lunar surface must be greater than 400 N. The weight in lunar gravity (400 N / 1.622 m/s^2 = 250 kg) leads to a minimum 250 kg vehicle mass. [Bartlett08]

The Scarab rover's chassis and suspension was designed around the drill. This component of the payload is significant in mass (50 kg) and imposes forces on the chassis during transport and while interacting with the ground.

Scarab's chassis allows it to passively conform to the terrain. The suspension has active and passive elements for improved traction on slope terrain. The active element, as previously discussed with respect to drilling, allows the rover to level the body, leading to increased stability and traction efficiency. The passive element, sometimes called an averaging (or differencing) linkage provides a mechanical release allowing the two rover suspension side-frames to pivot independently.

The averaging linkage ensures the body is pitch-averaged between the rocker arms. Scarab's body has three contact points. On either side, the body is connected to the pivot in the rocker arms. On top, the body hangs from the differencing linkage. This linkage runs across the top of the body and also connects to the rocker arms. Scarab actively controls its roll using the rocker arms by changing the height of each

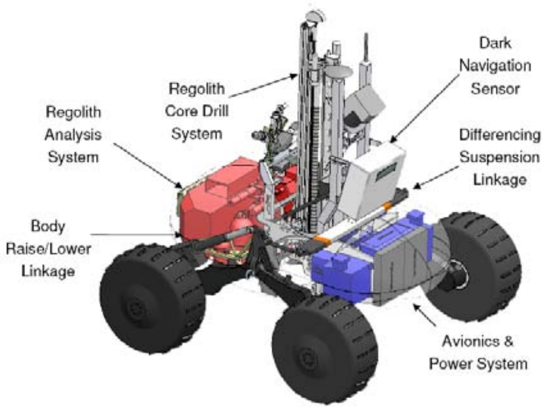

Figure 2. Scarab rover configuration showing placement of sensors, avionics, and payload. There are drive motors in each of four wheels and two linkages for adjusting sideframe height. An averaging linkage allows all four wheels to maintain ground contact in rough terrain.

Table 1. Scarab Rover Specifications

Mass	280 kg
Weight	2740 N Earth surface
	450 N Lunar surface
Locomotion speed	3 - 6 cm/s
Wheel diameter	65 cm
Track width	1.4 m
Wheelbase	0.8 - 1.4 m
	1.2 m nominal
Aspect ratio (track/wheelbase)	1:1.0 low stance
	1:1.2 nominal stance
	1:1.7 high stance
CG planar location	On geometric center
CG height	0.48 m low stance
	0.64 m nominal stance
	0.74 m high stance
Static pitch-over	56° low stance
	43° nominal stance
	30° high stance
Static roll-over	61° low stance
	53° nominal stance
	49° high stance
Maximum straddle	0.55 m
Minimum straddle	0.00 m (ground contact)

side independently, thus controlling the roll. In contrast the pitch is passive. Scarab's wheels conform to the terrain, which rotates the rocker arms and swivels the differencing linkage. The linkage is constructed such that the body is forced to move up or down by half the angle between the two rocker arms. As the center-of-mass of the rover is located midway between the side frames, equal loading occurs on all four wheels even on drastically uneven terrain.

Mobility Experiments

Testing Scarab in the field has been critical in proving the concept for lunar mobility and quantifying performance. Experiments have been conducted in numerous conditions with several findings of importance. However it is understood that continuing experimentation is needed to provide the data for a fully validated performance model and, most important, to enable extrapolation of terrestrial results to the lunar environment.

Moses Lake Sand Dunes in Washington was chosen as a test site for its varied terrain (slopes, pits, etc.), low moisture content, varied soil types (strengths, size distribution) and wide open space. These qualities provided grounds for mobility traction testing and long distance dark navigation traverses. Steep slope ascent/descent in loose soil and tests of new slope climbing techniques and algorithms were the focus of these field tests in June 2008.

Another lunar analogue site, located on Mauna Kea, Hawaii, is at high altitude with dry, deep, basaltic volcanic ash allows repeated mobility and navigation experiments. The soil composition and mechanical properties at this site were ideal for the regolith sampling hardware experiments. The objectives of these tests in November 2008 were to demonstrate roving, drilling, sample acquisition, processing and analysis. The rover was able to autonomously traverse kilometers of rough terrain, inspect a drill site, drill to 1 m depth, process the core samples and analyze the composition of the captured soil and demonstrate extraction of water from soil.

Characterization of Scarab as a system for difficult terrain mobility was first quantified in the laboratory in statics tests and in sandboxes. [Bartlett08] The independently actuated rocker arms of the Scarab rover allow for actively controlled center-of-mass shifting. The JPL Sample Return Rover has similar capability [Iagnemma00]. Benefits of this feature include decreased slip during cross-slope maneuvers. Scarab was tested normal to the slope and leaning to maintain vertical posture with cross-slope of 10˚, 15˚and 20˚. A surveying total station tracked a prism on the rover to millimeter accuracy and recorded instantaneous slip measurements. The outcome, expressed as percentage downhill slip with respect to cross-slope distance, appears in Table 2.

Table 2. Downhill Slip

Slope	Normal	Leaning	Change
10˚	6%	2%	-4%
15˚	22%	8%	-14%
20˚	37%	15%	-22%

The considerable decrease in downhill slip (2.5x at 20°incline) arises from increased traction due to equalization of wheel loading in highly cohesive soils and edging effects of the wheel profile in frictional soils. The significance of this outcome lies in the ability to descend and navigate steeper slopes with while maintaining adequate control authority.

A widely used metric for measuring the total tractive ability of a vehicle is drawbar pull. This is the value the vehicle can pull in a specified material while maintaining forward progress. The maximum drawbar pull value corresponds to the inflection in the load/slip curve where the soil fails and the wheel enters the high slip regime. This value is informative when comparing different designs and also used for determining the slope a vehicle can ascend for the specified material. Drawbar pull experiments were conducted in Washington and Hawaii to evaluate of the effects of rover mass properties, wheel design, and soil properties on tractive performance. (Fig. 3) Both the drawbar pull value and power values derived from this test are used as metrics to determine performance.

The key observations are the range of tractive values that occur with changing soil properties. For high bearing strength materials, the level of looseness and compaction does result in slightly varied traction and power (shear strength and sinkage respectively). The overall mass also has little effect on the normalized drawbar pull value (percentage of vehicle weight) although with extremely low bearing strength materials, this does not hold true as a result of excessive sinkage. The shear strength comes from cohesiveness and internal friction. As a result, the drawbar pull values can be representative of slopes achievable for only highly cohesive material as the normal loading of the surface is constant throughout testing. The most significant effect on traction has resulted in wheel design. Experiments involving different traction surfaces, wheel diameter and ground pressures have shown a large range of drawbar pull values. Differences of 50% have been achievable through traction surface/grouser modifications. Lowering ground pressure and reducing sinkage has moderate effects on traction but results in large differences in driving power (up to 50% during experiments). Drawbar pull tests performed as lab and field experiments have highlighted wheel design as a leading element in tractive and power design requirements. (Table 3.) This is important because wheel design is generally independent of the suspension design and can be optimized for traction and power efficiencies.

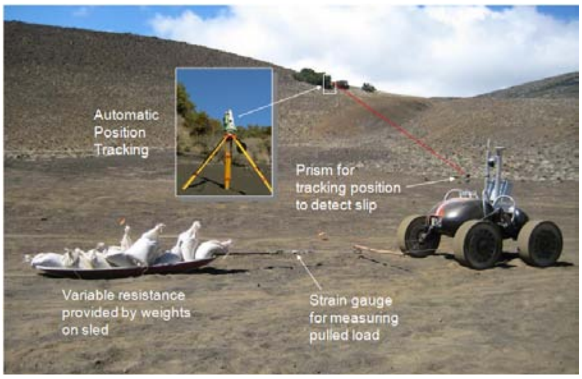

Figure 3. Drawbar pull experimental setup. Weight is added to the sled with the rover in motion while slip is continuously monitored.

Active control methods can also lead to increased tractive performance.

Techniques such as “inch-worming” can increase the mobility of a rover. (Fig. 4) To begin the cycle of inch-worming, the body lowers while expanding the wheel-base and rolling the front wheels forward while the rear wheels remains static. In the second half of the cycle, the body raises and the wheel base shortens while the rear wheels rolls forward and the front wheels remains static. Non-rotating wheels provide a fixed point of reaction with no slipping. To achieve these benefits, Scarab's inch-worming algorithm relies on eliminating the compaction resistances on two of the four wheels, by remaining static with respect to ground, for a resulting net tractive increase. Experimentally we have found that the inch-worming technique is best suited when wheels become entrenched under high slip. It allows the rover to move forward (or back up) out of this situation.

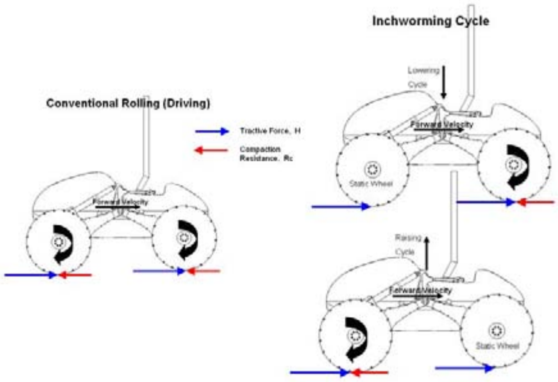

Figure 4. Conventional rolling versus inch-worming where one wheel pair is synchronized to the side-arm expansion/contraction and the other reacts forces into the ground.

Actively-positioned center-of-mass can also increase steepness of slopes traversable: distributing the load amongst the rover’s wheels leads to more efficient traction. Center-of-mass shifting (body leaning) was tested and heading slip, the slip in the commanded direction with respect to the commanded velocity, showed increase the steepness of slopes ascendable. The experiments were conducted with a 25˚ angle attack from the horizontal. This value was determined experimentally to have adequate uphill progress and low slip. It was shown that with the transformable suspension of the Scarab rover, slopes of 20˚loose, dry, volcanic ash can be ascended with low risk.

Table 3.	Soil Depth	Lunar Wheel	Rubber Tire	Difference
Locomotion Power	7.5 cm	100W, 100W w/grouser	158W	0.58
	5.0 cm	95W	160W	0.68
	2.5 cm	95W	103W	0.08
	1 cm	98W	117W	0.19
Maximum Drawbar Pull	7.5 cm	23%, 32% w/grouser	28%	0.18, 0.28
	5.0 cm	24%	32%	0.25
	2.5 cm	32%	39%	0.18
	1 cm	33%	50%	0.34

Navigation Experiments

Figure 5. Scarab navigating in darkness. Laser scanner perceives terrain ahead and an underbody optical velocity sensor detects slip.

Scarab navigates autonomously on kilometer scales. A route planning algorithm generates intermediate goals (typically with 100 m spacing) and the operator may specify multiple goals, Scarab will reach each goal in order.

Scarab uses an onboard inertial measurement device (Honeywell HG1700) and optical ground speed sensor to enable it to estimate position and velocity with 1 - 3 % error on distance traveled. (Fig. 5) Laser ranging provides measurements to build models of the surrounding terrain to detect obstacles and then determine efficient and safe paths. (Fig. 6)

Scarab periodically scans the terrain using a laser rangefinder developed by Neptec Design Group. [Neptec08] Previous autonomous rovers have used stereo cameras for high density terrain observations with low power. [Wettergreen08] In the scenario that Scarab addresses, polar lunar craters, there will be significant areas of slope and crater floor in shadow and in some cases, perpetual darkness so active sensing devices are required. Scarab acquires a scan after appreciable driving (more than 3 m) or turning (greater than 10°) or after time has elapsed (more than 100 sec). The sensor produces a dense array of ranges and takes several seconds, so motion must stop to avoid warping the data. The navigation algorithms assume a static world, meaning the terrain does not change between scans. Each 3D cloud of range points is incorporated into the terrain model. The range points are filtered (to remove

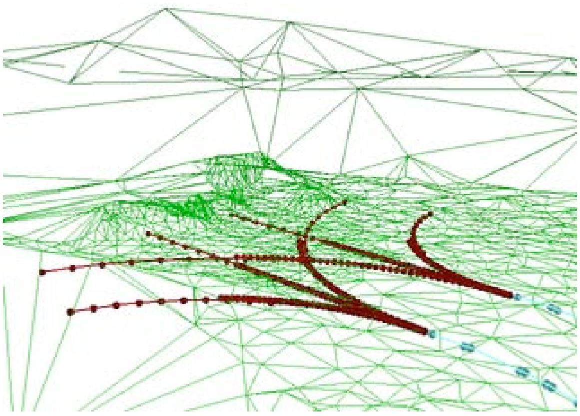

Figure 6. Mesh terrain model used to represent obstacles and to evaluate and refine the path. Modeling and evaluation iterate to navigate to the goal.

noise and artifacts) and transformed into the vehicle's coordinate frame. Coarse data reduction on the point cloud is applied and the point cloud is transformed into a mesh. The mesh is then further reduced to eliminate redundant data. Finally the mesh is aligned with prior data to generate the terrain model that is used to identify obstacles and select the best path to the goal. Many candidate vehicle motions are evaluated in the near- and far-field. The near-field analysis involves simulating vehicle motion on the mesh to identify collision and slope hazards and assess their severity. The far-field analysis applies heuristic search to estimate the progress each potential move will make toward the goal. A cost function combines safety in the near-field with progress in the far-field.

Our experimental approach has been to conduct 1 km traverses in a variety of terrains with progressive improvements to algorithms. At both the Moses Lake and Mauna Kea sites, Scarab autonomously completed the following objectives: travel over 3 km, perform 2 night traverses and simulate crater

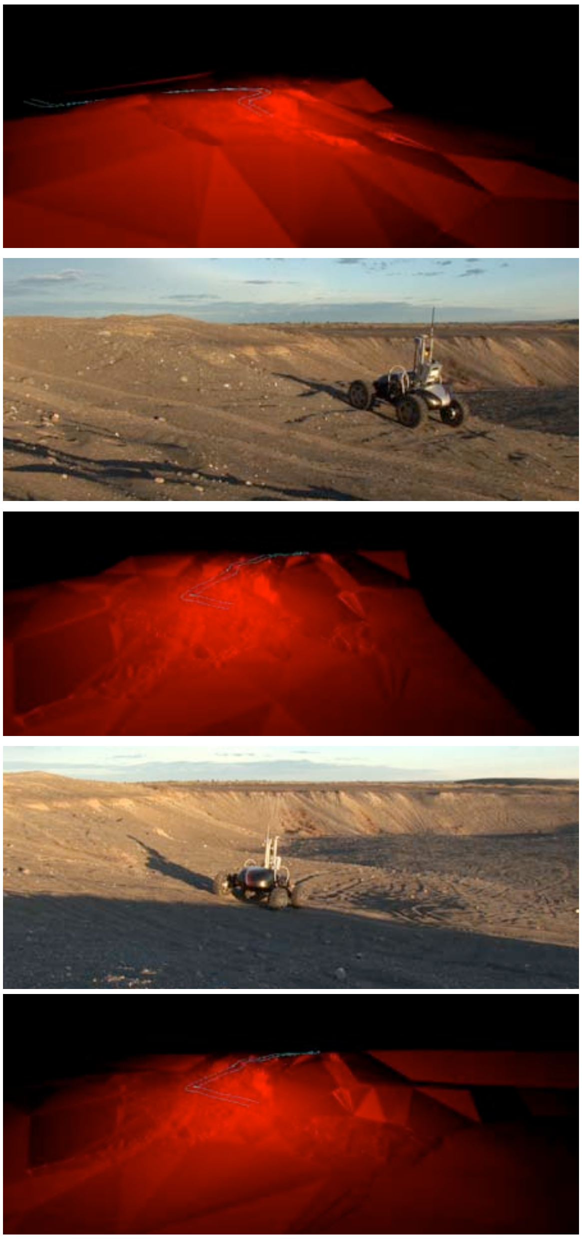

Figure 7. Autonomous descent into a large pit. Rendered views are terrain model with path of rover at rim, intermediate, and viewing the floor. Images show rover during descent. Scarab discovered a moderate slope and reached the floor autonomously.

descent. Traverses are kilometer scale and performed after sunset, they account for most of the total distance traveled at each site. Crater descent was conducted with a long (100 m) traverse that included descending a steep (10°) slope.

Scarab completed a total of 3.6 km in 27 traverses in Washington. The first dark traverse was 1.2 km with 4 interventions due to sensor faults and one due to a controller error. These faults are recoverable; they do not jeopardize the rover and are easily resolved by resetting a device. A second dark traverse used an alternative navigation algorithm [Pedersen08] and completed 1.1 km with two interventions due to localization errors.

Scarab traveled 3.0 km in 20 traverses at Mauna Kea, most of this was accomplished during the two overnight traverses. The first dark traverse was split into two parts; after 199 m the traverse was paused for logistic reasons and later Scarab resumed for an additional 779 m before stopping due to a software error. The second overnight traverse was also split in two; the first part was 312 m and stopped on a software error, the second was 989 m and ended with a CANBus fault. All of these errors are recoverable remotely.

At each site, Scarab autonomously completed a simulated crater descent using available analogue terrain. At Moses Lake, Scarab drove into a 9 m deep pit with 10°-20°sloped sides. (Fig. 7) This was safely accomplished including two undirected switchback maneuvers. At Mauna Kea, Scarab repeatedly drove down a winding drainage channel. The route was over 100 m long and descended over 25 m with an average grade of about 10°.

Traverse termination conditions for both field tests are shown in Chart 1. No interventions were required to stop the vehicle from driving into a hazard (zero emergency stops). At Moses Lake, most traverses (15 of 25) ended with a recoverable fault. On Mauna Kea the navigation method had improved and most traverses ended by reaching the goal (8 of 20) or stopping the traverse for other reasons (6 of 20). Recoverable faults are those that could be remotely corrected and thus would not be mission ending in a lunar scenario.

These results are far from perfect but indications are that reliability is improving and will reach the level of previous planetary rover prototypes.

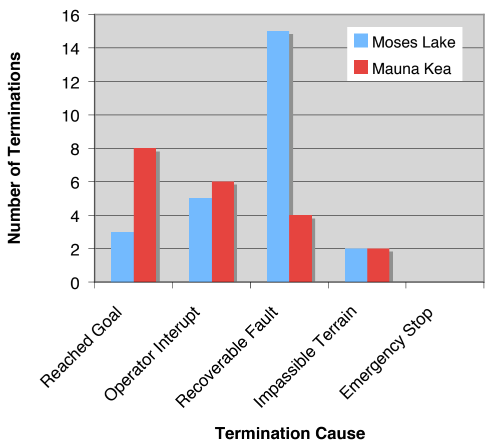

Chart 1. Termination conditions in autonomous navigation experiments.

Conclusion

The Scarab rover has been uniquely configured for the transport and stabilization of a coring drill and associated soil analysis instruments. The benefits of central-mounting and active body height and roll control are apparent in deployment of the drill and improved ability to ascend and descend cross-slope.

Field experimentation has quantified drawbar pull and slope climbing ability as well as power required for these activities under a variety of soil and terrain conditions. Field demonstrations have also proven the capability of the laser-based navigation system for kilometer-scale autonomous traverse, including autonomous descent into a crater. In total the mobility and navigation requirements for a lunar surface prospecting mission have been demonstrated in analogue terrain.

Acknowledgments

We gratefully acknowledge the contributions of our technical team and the assistance of Phillipe Ayoub, Paul Bartlett, Deborah Sigel, John Thornton, Chuck Whittaker, and William Whittaker. This research was supported by NASA under grants, NNX07AE30G, John Caruso, Project Manager, and NNX08AJ99G, Robert Ambrose, Program Scientist.

References

[Bartlett08] Bartlett, P., Wettergreen, D., and Whittaker, W., “Design of the Scarab Rover for Mobility and Drilling in Lunar Cold Traps,” International Symposium on Artificial Intelligence, Robotics and Automation in Space (iSAIRAS), Los Angeles, February 2008.

[Iagnemma00] Iagnemma, K., Rzepniewski, A., Dubowsky, S. et al., “Mobile robot kinematic reconfigurability for rough-terrain,” SPIE 2000.

[Neptec08] http://www.neptec.com/Neptec_TriDAR.html

[Pedersen08] Pedersen, L., et al., “Dark Navigation: Sensing and Rover Navigation in Permanently Shadowed Lunar Craters,” iSAIRAS, Los Angeles, February 2008.

[Sanders09], Sanders, G., et al., “In Situ Resource Utilization (ISRU) Program,” AIAA Aerospace Sciences, Orlando, January 2009.

[Spudis06] Spudis, P., “Ice on the Moon”, The Space Review, November 2006.

[Wettergreen08], Wettergreen, D., et al., “Long-distance Autonomous Survey and Mapping in Robotic Investigation of Life in the Atacama,” iSAIRAS, Los Angeles, February 2008.

[Wettergreen09], Wettergreen, D., et al., “Design and Experimentation of a Rover Concept for Lunar Crater Resource Survey,” AIAA Aerospace Sciences, Orlando, January 2009.