Human Exploration of Asteroids, the Moon and Mars Using Robotic Arm-Equipped Pressurized Vehicles

Pascal Lee[1,2,3], Sean Dougherty[4], Tom McCarthy[4], Terry Fong[3], Stephen J. Hoffman[5,6], Ed Hodgson[7], Kira Lorber[1,8], Robert Mueller[9], John W. Schutt[1], Jesse T. Weaver[1], and Luis Alvarez[1,10]

[1]Mars Institute, NASA Research Park, Bldg 19, Suite 2047, Moffett Field, CA 94035-1000, USA; Ph (408) 687-7103; email: pascal.lee@marsinstitute.net
[2]SETI Institute, 189 Bernardo Ave, Suite 100, Mountain View, CA 94043, USA
[3]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, USA
[4]MDA Information Systems, Inc., 1250 Lincoln Ave, Pasadena, CA 91103, USA
[5]SAIC, 2200 Space Park Drive, Suite 200, Houston, TX 77058, USA
[6]NASA Johnson Space Ctr, MS ZS, 2101 NASA Pkwy, Houston, TX 77058, USA
[7]Hamilton Sundstrand Corp., 1 Hamilton Road, Windsor Locks, CT 06096, USA
[8]University College London, Gower Street, London WC1E 6HJ, United Kingdom
[9]NASA Kennedy Space Center, Surface Systems Office, NE-S, FL 32899, USA
[10]College of San Mateo, 1700 W. Hillsdale Blvd, San Mateo, CA 94402, USA

ABSTRACT

During the 2011 summer field campaign of the NASA Haughton-Mars Project at the Haughton impact crater site on Devon Island in the high Arctic, field tests were conducted of the use of a robotic arm system integrated to Humvees serving as analog pressurized vehicles for the human exploration of near-Earth asteroids, the Moon, and Mars. The goal of these field tests was to begin assessing how field geology, including sample acquisition, might in some cases be conducted effectively from the confines of a pressurized vehicle (in intra-vehicular or IVA mode) without the crew having to always go out on EVA. Preliminary findings suggest that, particularly at sites where rocks and soils available for sampling occur mostly as loose rubble or "float" (as with planetary regoliths), the use of a robotic arm can allow efficient collection and characterization of high quality samples. An important implication of the finding for future space exploration architecture development, if confirmed through further field tests, is that the number and frequency of EVAs needed for sample acquisition during planetary vehicular traverses might be reduced from current assumptions. Wear and tear on EVA suit and suit-port systems, mission operations complexity, crew exposure to space radiation, and planetary protection concerns, might all be significantly reduced if robotic-arm assisted sample acquisition in IVA mode became available as an effective option for science operations.

INTRODUCTION

Small, nimble pressurized vehicles are anticipated to be central architectural elements in the future human exploration of Near-Earth Objects (NEOs), the Moon, and Mars. Compared to non-pressurized mobility systems, pressurized vehicles will enable longer duration, longer range, more flexible, and safer human exploration of these planetary bodies. NASA and other space agencies are currently investigating how best to use pressurized vehicles for exploration operations, particularly science operations, as part of identifying pathways along the Global Exploration Roadmap (Hoffman et al. 2011, ISECG 2011).

Recent field tests investigating crewed pressurized vehicles for science operations have focused on scenarios in which the vehicles are used primarily as a means of *transportation* allowing crews to access sites of scientific interest, where they then go on EVA (extra-vehicular activity) to conduct fieldwork. Although science payloads were integrated to the vehicles, traverses remained planned as a sequence of EVA stations (Apollo-style), with IVA (intra-vehicular activity) science operations limited to scouting and the gathering of contextual information once arrived at EVA sites (Lofgren *et al.* 2010). However, as suggested following earlier field studies conducted at the Haughton-Mars Project (HMP) on Devon Island in the High Arctic, pressurized vehicles may be used as powerful science tools in and of themselves (Lee 2010, Lee *et al.* 2010, Lee *et al.* 2011).

We report here on the results of a new field study conducted at HMP during the 2011 summer field campaign in which the potential value of using pressurized vehicles as integral field science tools was further investigated, specifically with focus on the use of pressurized vehicles equipped with robotic arms for sample collection and examination (Figure 1).

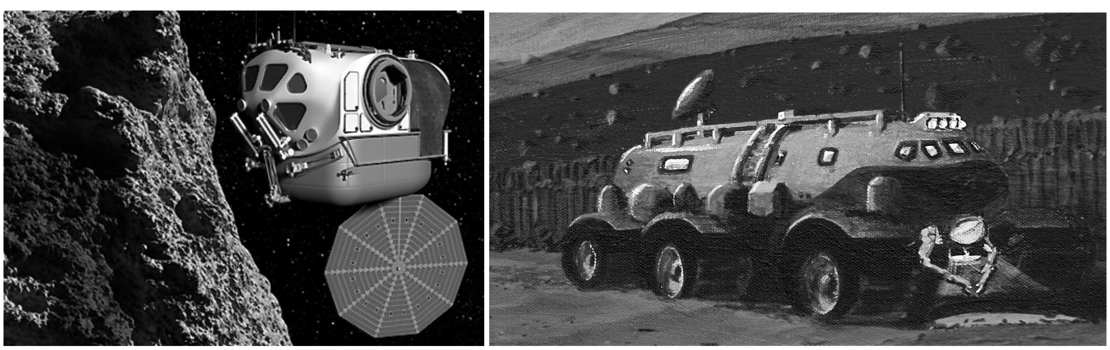

Figure 1. Robotic arm systems on pressurized planetary exploration vehicles. Left: Arms and legs systems (retracted) on a Multi-Mission Space Exploration Vehicle (MMSEV) near an asteroid (NASA). Right: Robotic arm system on a pressurized rover on Mars (Artwork by Pascal Lee).

A Key Lesson from Apollo. A central and common task in science operations anticipated on NEAs, the Moon, and Mars, will be sample collection. The Apollo program offers a very important, yet often overlooked, lesson in this regard: 95% of all samples collected during the Apollo missions were *float*, i.e. rock samples found and picked up as isolated loose fragments "sitting" on the lunar surface, disconnected from any immediately visible original bedrock or outcrop (G. Lofgren, *pers. comm.*). Because almost only float was encountered on the Moon, collecting samples on Apollo required mainly only a scoop; the rock hammer was almost never used (H. Schmitt, *pers. comm.*) (Figure 2).

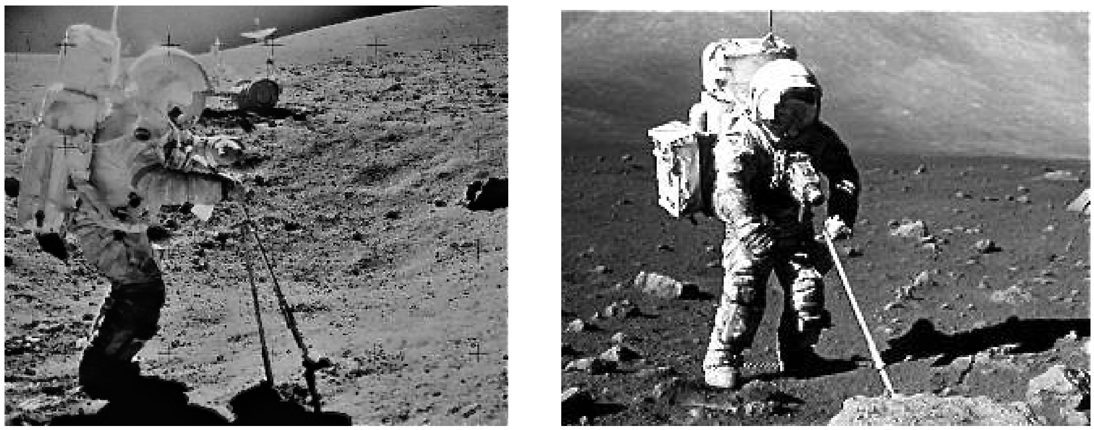

Figure 2. Scooping up float. On Apollo, 95% of all samples collected were *float,* i.e. free-floating rocks. They were picked up with a scoop, not extracted from an outcrop with a rock hammer. Left: Apollo 16 astronaut John W. Young using the scoop. Right: Apollo 17 astronaut-geologist Harrison H. Schmitt using the scoop (NASA).

In terrestrial geology, float is usually considered to be of lesser value as a sample compared to a piece of rock extracted directly and freshly from an outcrop, because float, by definition, lacks immediate context and often tends to be weathered. Considering too that outcrops are generally available and accessible on Earth, float is viewed as subpar sample material that is actively avoided. But on rocky planetary surfaces subject to intense impact processing, float is often all that is available and can be of critical value to collect.

On the Moon, although Apollo focused mainly on the exploration of *mare* sites, this situation of float being in practice the best type of samples available to collect, is likely to remain true even when the lunar highlands are explored.

On Mars, while the Mars Exploration Rovers have shown that bedrock is often exposed and accessible, a large number of sampling opportunities still come in the form of float. Meteorites, in particular, appear to be common opportunistic finds.

On NEOs, and in particular small NEAs (Near-Earth Asteroids) as might be visited by humans, surfaces made of impact-generated loose rubble are likely very common. This was the case of NEA Itokawa as revealed by JAXA's Hayabusa robotic spacecraft mission.

The best strategy for sample collection on anticipated future human missions to NEAs, the Moon, and Mars is therefore to be prepared not only for the ideal but likely rarer opportunity to collect samples from actual outcrops, but for optimizing the much more common opportunity of sampling float.

EVA *vs* IVA. Compared to extracting a sample from an outcrop, acquiring a float sample is relatively simple. The rock or soil sample just needs to be picked up or scooped up. Should an EVA be conducted each time a float sample is to be collected? EVAs on future human planetary exploration missions will undoubtedly be necessary for many tasks, including extracting samples from outcrops when possible. It will be important, however, to avoid conducting EVAs when they can be readily replaced by an IVA instead. EVAs from pressurized vehicles will be rendered relatively easy using a suit port approach, but they will always remain associated with substantial added risk and cost. An EVA subjects astronauts to higher radiation exposure than IVA, and incurs added cost in mission operations planning and support, crew rest, life support supplies, and suit wear and tear, particularly in dusty environments (*e.g.*, Gaier *et al.* 2009, Hodgson et al. 2011). Reducing the frequency of EVAs will also help address Planetary Protection requirements (Schuerger and Lee 2010).

While geologists engaged in planning human planetary exploration missions frequently emphasize the critical importance of astronauts having enough "boots on the ground" time, this emphasis should not be taken literally. Geologists on Earth typically need to hike and climb rugged terrain to reach outcrops, until they come to within an arm's length of fresh material to be examined and sampled. In the terrestrial context, boots on the ground time translates directly into more observation and sampling time. However, it is not actually "boots on the ground time" that matters, but the ability for a geologist to nimbly move and properly observe, sample, and examine geologic features and materials. What actually needs to get close to the ground and its rocks and soils are not an astronaut's boots, but his/her eyes (or extensions thereof), and his/her hands (or extensions of these).

Thus, the fundamental operational requirement for enabling humans to do field work effectively is not that they be on foot, but that they *be mobile*, *see well*, and *are able to select, collect, and examine good samples*. EVAs allow these requirements to be met, but so would *a pressurized vehicle that is nimble, affords good visibility, is adequately equipped and instrumented to allow dexterous sample collection in IVA mode using a robotic arm system with sufficiently high degrees of freedom (DOFs).* Such a vehicle would be the functional equivalent of a multiple-person spacesuit.

In order to begin testing this new science concept of operation, one in which astronauts would be conducting most of their surface observations and sample collection in IVA mode, we initiated a series of field tests to investigate the challenges and requirements of this approach.

GOALS, OBJECTIVES, AND METHODOLOGY

Goals. The main goals of our research were to:

1) Evaluate in a real and relevant field setting the feasibility and challenges of conducting sample collection and examination using a basic robotic arm system.
2) Define a set of preliminary requirements for a future robotic arm system on a pressurized vehicle that would ensure the success of an IVA-based science concept of operations.

Objectives. To achieve the above goals, we pursued the following set of objectives:

A) Create an experimental platform to investigate the design, operation, and training requirements for robotic arm systems on pressurized exploration vehicles.
B) Obtain a quantitative estimate of the amount of training time needed to achieve basic proficiency in the use of a robotic arm system on a pressurized vehicle.
C) Identify basic challenges and requirements associated with the design and operation of a robotic arm system on a pressurized planetary exploration vehicle.

Objective A was met by integrating an existing 4 DOF robotic arm system to a pressurized vehicle simulator, and by deploying the arm to collect samples in a realistic and relevant planetary analog field setting.

Objective B was met by providing actual training in the field to a group of 20 test subjects in the operation of the robotic arm system using the above experimental platform. Training was provided once per individual, on a one on one basis.

Objective C was met by observing the performance of, interviewing, and collecting feedback from, the same group of trained test subjects during and immediately following their experience using the robotic arm to collect samples.

Analog Facility: Haughton-Mars Project Research Station, Devon Island, Arctic. The planetary analog field site and test facility chosen for the experiment was the Haughton-Mars Project (HMP) Research Station, at 75^{o} 26’ N, 089^{o} 52’ W, on Devon Island, High Arctic. The HMP is an international multidisciplinary field research project centered on planetary science and exploration studies at the Haughton meteorite impact crater site on Devon Island. Devon is a cold, dry, windy, rocky, dusty, unvegetated, UV-exposed, ground-ice-rich, and impact-scarred polar desert. 85% of rock samples collected there are float, as surface materials are dominated by impact, freeze-thaw, and glacier generated rubble, not bedrock (Lee et al. 2011). The site is an established Moon and Mars analog used by NASA and the Canadian Space Agency. The site is also uniquely suited for studying key aspects of NEO exploration, in particular given the combined presence of impact rubble and ice (Figure 3).

Figure 3. HMP as a Near-Earth Asteroid Analog. Left: Image of the *Moon-1 Humvee Rover* superimposed on an image of the boulder-laden surface of NEA Itokawa, to scale. Right: Original image of the *Moon-1* in a boulder field at Haughton with a similar block size distribution. (JAXA and NASA HMP-2011/P. Lee).

Analog Pressurized Vehicle: HMP *Mars-1 Humvee Rover*. The HMP uses modified maxi-ambulance versions of the High-Mobility Multipurpose Wheeled Vehicle (HMMWV) or Humvee to simulate science operations using small pressurized vehicles. During the HMP-2011 campaign, the HMP's *Mars-1 Humvee Rover*, served as the robotic arm test vehicle (Figure 4). The *Moon-1* was a back-up.

Robotic Arm System. A preexisting 4 DOF robotic arm system developed by MDA Information Systems, Inc. of Pasadena, CA was used to support the field experiment. The end effector available was a simple 2-prong gripper with a force/torque sensor.

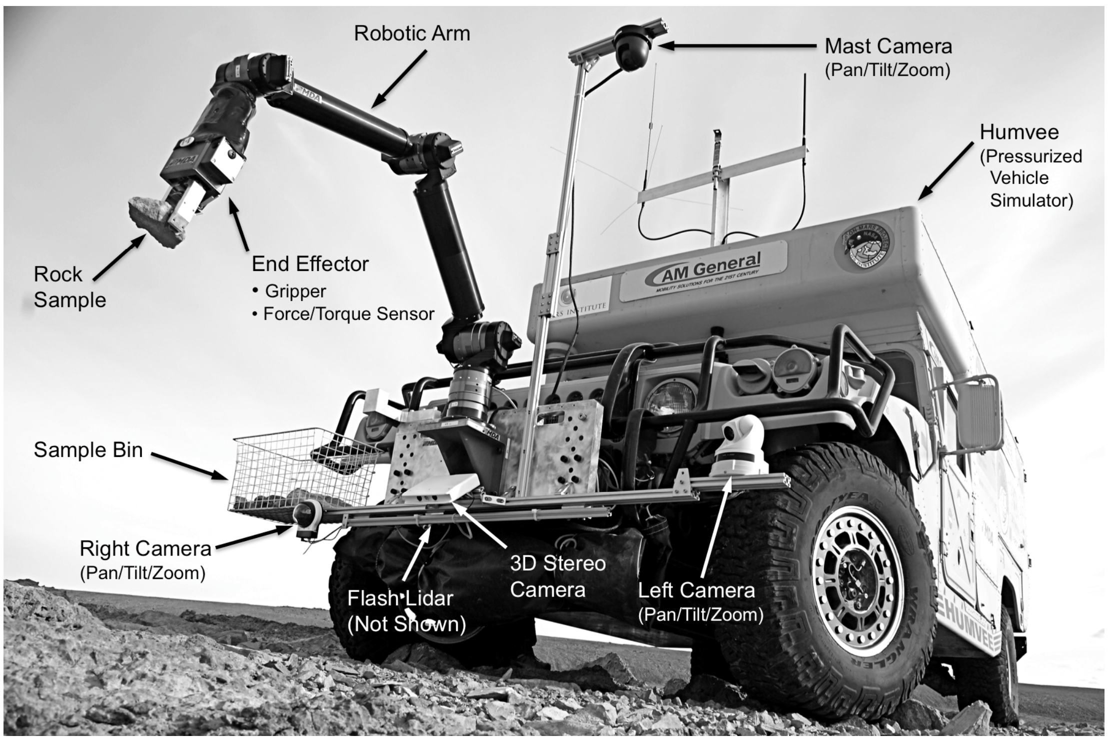

Figure 4. Robotic Arm System on HMP Mars-1 Humvee Rover. Annotated image showing key robotic arm external hardware elements. (NASA HMP-2011/P.Lee).

Figure 5. Robotic arm control workstation in the Mars-1 Humvee Rover cockpit. MDA engineer Sean Dougherty provided on-site training (NASA HMP-2011/P. Lee).

RESULTS

Integration of the MDA robotic arm system hardware with the HMP's *Mars-1 Humvee Rover* was well planned and occurred without major issues (Figure 5).

During traverses, terrain features and geologic formations, including outcrops and individual boulders and rocks, were adequately approached and examined over a range of spatial scales (10^2 m to 10^{-2} m) (Lee et al. 2011). Selection of the sample collection patch (area that would be accessible to the arm once the vehicle was stopped) occurred by direct visual inspection of the geologic site through the vehicle's windows. Once stopped, the sample collection patch was no longer visible directly through the vehicle's windows, as it would then be below the hood of the Humvee (Figure 6). Actual sample collection was then conducted based on imaging acquired by the four camera systems and the lidar supporting the robotic arm.

Acquiring any sample within a sample collection patch was generally easily feasible using the 4 DOF arm and simple gripper. Acquiring a specific sample within the patch, however, often presented challenges because of substantial imbrication of individual rocks in the rubble. An extra 2 DOFs and the ability to have greater control of the gripper would have been extremely beneficial in this situation.

Once picked up, samples were brought up to the windshield where they were visually examined before getting dropped into a sample collection bin (Figure 7).

The following subsection provide a summary listing of basic requirements for a pressurized vehicle robotic arm system stemming from our study.

Figure 6. Robotic arm gripper closing in on a sample. (NASA HMP-2011/P. Lee).

Figure 7. Visual examination of a sample. (NASA HMP-2011/L. Alvarez & P. Lee).

Arm System Design.

1) A 6 DOF arm providing a reach of 1.75 m to 2 m (25 to 50% longer than the one tested at HMP-2011) will offer adequate flexibility, range, and speed of operation.
2) The arm's end effector should include a gripper and a scoop. The gripper should open from 10 cm to zero with fine control, and provide feedback on the force applied.
3) Collision avoidance measures and limit warnings are critical for arm safety.
4) Force/current accommodation is necessary so the arm cannot damage itself. Such motion/current limiting capability makes arm operations safer, easier, and faster.
5) A gamepad controller without haptic feedback was preferred over a falcon haptic controller and may facilitate general positioning, but it can present significant danger to the arm if there is no feedback from ground contact forces. If the ground is contacted, there should be haptic feedback of moments (more so than translations).
6) Need to decouple the arm's operating axes and have additional coordinate frames and modes, e.g., to "fly the end effector", to avoid confusing coordinate frames.
7) A "Go to Target" commanding capability via screen touching or view clicking will facilitate and accelerate arm operations. Once the end effector is in proximity to a target, an option should exist to switch to slower arm motion velocities.
8) Good quality color cameras, lighting, laser ranging, and laser pointers should be used to provide scale, outline workspace, and show the terrain in both virtual and real camera views. This will help estimate the size of targets and assess their depth/distance. 3D sensors are helpful. 3D stereo imaging and lidar should be fully integrated into the arm system. Pan & tilt imagers should report their positions.
9) End effector-mounted color cameras are critically important for in-situ sample examination and gripper or scoop positioning, and should be of good quality.
10) A scene modeler is needed to record and reconstruct the arm operation scene.
11) The ability to take screen shots of a target scene, and also to return to an earlier location or arm position by touch screen is helpful.
12) The arm's power system should be decoupled from that of the vehicle itself.
13) The arm system's boot up and error reset procedures must be streamlined to facilitate and speed up arm operations.
14) Given the potentially high frequency of sample examination needs in some locales, the robotic arm operations workstation, including the arm controller interfaces and displays, should be designed ergonomically.
15) An interface (platform with controlled lighting) allowing collected samples to be visually examined up close at hand lens scales prior to their storage is needed.

Arm Operations. With minimal training (30 to 60 minutes), it was possible for all test subjects at HMP-2011 to acquire a sample, from beginning to end, in 20 to 40 minutes. With additional training and reasonable hardware upgrades, sample acquisition, once the vehicle is in position, will require no more than 5 to 10 minutes.

The above time requirements may be compared to those required for EVAs. Combining EVA simulation experiences from Desert-RATS and HMP, a reasonable estimate of the total time overhead for each EVA using suit-ports, from donning-undock (egress) to redock-doffing (ingress), is 20 minutes (*e.g*., Hodgson et al. 2011).

Table 1 compares total times required for sample collection in EVA and IVA modes, the latter via the use of a robotic arm system. For the EVA, we assume: 20 min for egress plus ingress; 10 min for getting into position at the sample location and returning to the vehicle, per sample; 5 min for actual sample collection and documentation, per sample. For IVAs, we assume: 10 min for vehicle positioning, per sample; 10 min for sample collection and documentation, per sample.

Table 1. Sample collection total time requirements in EVA and IVA modes

Number of Samples Collected	EVA (1 Sortie)	IVA (Robotic Arm)
1	35 min	20 min
2	50 min	40 min
3	65 min	60 min
4	80 min	80 min

Although some simple (possibly simplistic) assumptions were made in the above table, the basic message is that, during the course of a pressurized vehicle traverse, the opportunistic collection of a single float sample will take almost 50% less time if a robotic arm operated in IVA mode is used compared to going out on an EVA to perform that same task. For more samples at the same site, the difference in time requirement between the two approaches, assuming all samples are float, diminishes. Resource consumption impact and risk, however, remain highest with the EVA approach.

CONCLUSION

Analog pressurized rover field studies at the Haughton-Mars Project (HMP) on Devon Island suggest that productive planetary field science investigations can be conducted by humans from within the confines of a highly mobile, well-equipped, and well-instrumented pressurized vehicle. Being able to conduct quality fieldwork in mostly IVA mode on NEAs, the Moon, and Mars, may significantly reduce requirements on the frequency of EVAs and make surface exploration safer, more productive, cost-effective, and sustainable.

The present study further supports the concept of using pressurized vehicles as *research vessels* from which *most* of the field science would be conducted in IVA mode. This approach may, in practice, offer a more optimal and general approach to conducting field science using pressurized vehicles.

Specifically, the study reported here shows that effective rock and soil examination, and sample selection and collection can be performed assuming a 4

DOF robotic arm operating within a 180°, 1.5 m range in front of the pressurized vehicle, provided adequate side and top view imaging is available for guidance and sample inspection. However, a 6 DOF robotic arm system and the additional system requirements listed above would create a highly capable traverse sampling tool.

ACKNOWLEDGMENTS

This research was supported in part by the NASA ESMD Directorate Integration Office (now in NASA HEOMD) and a NASA SMD MMAMA grant to P. Lee at the SETI Institute. Additional support was provided by Mars Institute, NASA Ames Research Center Intelligent Robotics Group, AM General, MDA Information Systems, and Hamilton Sundstrand. Special thanks are owed to the HMP-2011 field participants who trained on, and operated, the robotic arm system. We also thank the Government of Nunavut, and the arctic communities of Resolute Bay and Grise Fiord.

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