Robotic Recon for Human Exploration

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Introduction

Robotic reconnaissance has the potential to *significantly* improve scientific and technical return from lunar surface exploration. In particular, robotic recon may increase crew productivity and reduce operational risk for exploration. However, additional research, development and field-testing is needed to mature robot and ground control systems, refine operational protocols, and specify detailed requirements.

When the new lunar surface campaign begins around 2020, and before permanent outposts are established, humans will initially be on the Moon less than 10% of the time. During the 90% of time between crew visits, robots will be available to perform surface operations under ground control. Understanding how robotic systems can best address surface science needs, therefore, becomes a central issue

Prior to surface missions, lunar orbiters (LRO, Kaguya, Chandrayyan-1, etc.) will map the Moon. These orbital missions will provide numerous types of maps: visible photography, topographic, mineralogical and geochemical distributions, etc. However, remote sensing data will not be of sufficient resolution, lighting, nor view angle, to fully optimize pre-human exploration planning, e.g., crew traverses for field geology and geophysics. Thus, it is important to acquire supplemental and complementary surface data.

Robotic recon can obtain such data, using robot-mounted instruments to scout the surface and subsurface at resolutions and at viewpoints not achievable from orbit. This data can then be used to select locations for detailed field activity and prioritize targets to improve crew productivity. Surface data can also help identify and assess terrain hazards, and evaluate alternate routes to reduce operational risk. Robotic recon could be done months in advance, or be part of a continuing planning process during human missions.

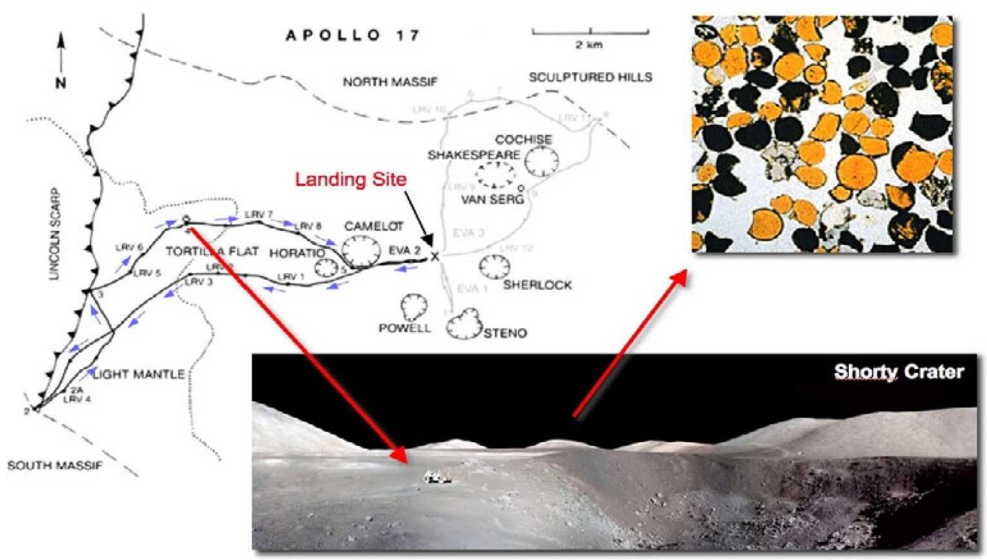

***Figure 1.** Orange glass discovered during Apollo 17 EVA #2, Station 4.*

For example, during Apollo 17 EVA #2, Harrison Schmitt discovered orange glass at Shorty Crater (Figure 1). This occurred at Station 4 and EVA time at the site was limited by walk-back constraints (based on EMU consumables). Had the presence of orange glass, or other pyroclastic concentrations, been identified in advance through surface reconnaissance, EVA #2 could have been planned with less time at preceding stations, so that more time could have been spent at Shorty Crater.

Robotic recon

We define robotic recon as operating a planetary rover under ground, or non-EVA astronaut, control to scout planned sorties prior to EVA activity. Scouting is well understood to be an essential phase of field work, particularly for geology, and can be: (1) traverse-based (observations along a route); (2) site-based (observations within an area); (3) survey-based (systematically collecting data on transects) or (4) pure reconnaissance [Fon08b]. Robot instruments provide measurements at resolutions and from viewpoints not achievable from orbit.

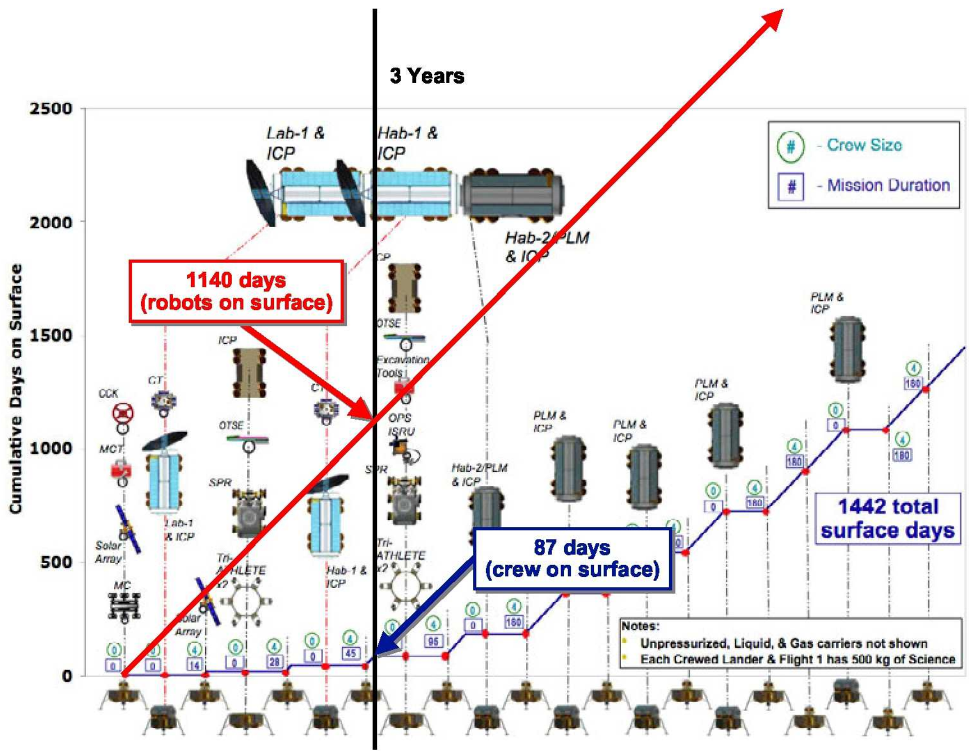

Figure 2. *Notional, ten-year lunar campaign with surface missions on six-month intervals. During the first three years, humans are on the Moon less than 10% of the time.*

National space policy currently directs NASA to return to the lunar surface with a series of missions spaced six months apart. Figure 2 shows a notional, ten-year lunar campaign, which is representative of NASA's current lunar architecture. During the first few years, crewed missions will be limited to "extended sortie" (one to two week) missions. During this period, humans will be on the Moon less than 10% of the time. This leaves as much as 90% time for robots to perform lunar surface tasks under ground control from Earth.

Robotic recon can be done far in advance to help develop overall traverse plans. We call this *advance recon.* Recon also can be done to refine an existing traverse plan, i.e., used to adjust priorities and modify timelines. We call this *lead scouting*. Advance recon offers more freedom in traverse planning, but requires significantly more time and greater spatial coverage. Lead scouting is a more constrained and requires less time to perform, but can still provide valuable and near-real time operational information for optimizing crew productivity.

We have begun studying robotic recon in a series of lab and analog field tests [Fon07, Fon08a, Fon08b]. A central part of our work has focused on refining operational concepts inspired by the Mars Exploration Rovers (MER), as well as human spaceflight, including Apollo, the Space Shuttle, and the International Space Station [Mis06, Sch05]. Our ground control approach integrates a science team similar to the Science Operations Working Group (SOWG) for MER and the "Science Backroom" from Apollo [Osb06].

Figure 3 shows the iterative traverse planning and execution process that we have developed for both advance recon and lead scouting. This process includes: (1) initial planning using *orbital* data (remote sensing) to create a baseline traverse plan, (2) interactive robotic recon to collect *surface* data and to update the traverse plan, and (3) crew traverse supported by a ground-based science team and data systems.

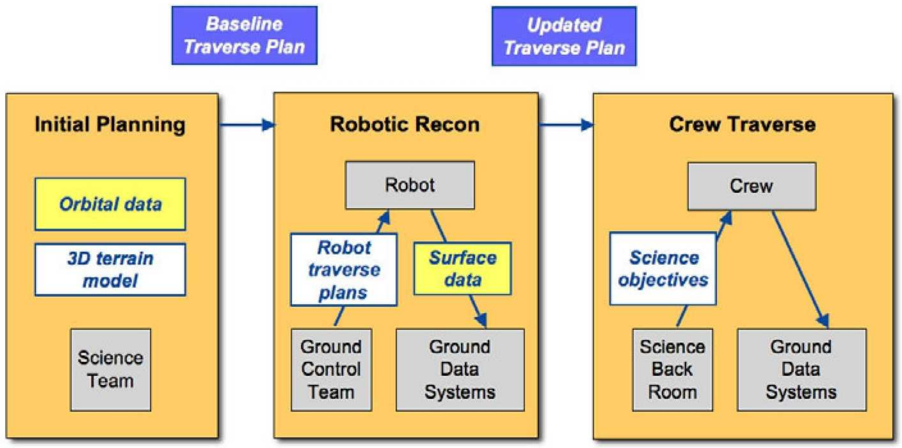

Figure 3. *Iterative traverse planning and execution process.*

Motivation

Robotic rovers will be needed on the Moon. Both the 2006 NASA Advisory Council's "Science Associated with the Lunar Exploration Architecture" meeting [NAC08] and the 2007 National Research Council's "Scientific Context for the Exploration of the Moon" report [NRC07] identify key roles for robots and recommend that research examine how robots can best assist humans on the Moon.

Humans themselves will be on the Moon. Because humans are able to explore the Moon *in situ*, robotic rovers do not need to be the primary (or sole) tools for science investigations. Instead, robots can be designed to do advance and preparatory reconnaissance that will enable humans to more efficiently and productively undertake field exploration science.

Substantial time is available for robotic recon. NASA's current lunar architecture includes substantial time and opportunity to use robots for surface activities. Unmanned crew rovers, for example, could be put to good use between human missions to significantly advance the planning of human vehicular traverses and EVAs. If constraints on EVA frequency (e.g., radiation exposure concerns) require some astronauts to skip EVA days, these astronauts could perform robotic lead scouting to prepare for future EVAs.

Remote sensing is often inadequate. Often, the only way to acquire measurements with very high-resolution (in spatial, spectral, or temporal dimensions), oblique views, and/or ground coupling is on the surface. Further, most geophysical analysis cannot be done from orbit, or only at extremely low resolution, as in the case of gravitational and magnetic anomalies.

We have very limited experience in the use robotic rovers as scouts for human exploration. While the notion of robotic recon is conceptually simple, scientific exploration has very limited experience with this concept of operations. To date, we have conducted the only NASA studies of robot scouting prior to human EVA: (1) during the 2008 Human-Robotic Systems field test at Moses Lake, WA [Fon08a]; and (2) a "robotic recon" experiment at NASA Ames (November 2008). Robotic scouting is *significantly* different from robotic exploration (e.g., MER) where the robot is used as the primary (and *only*) science tool.

Robotic recon helps address planetary protection. The future exploration of the Moon and Mars will require specific protocols to protect the crew, the environment, and the integrity of scientific investigations. Robotic rover scouting can be used to detect and localize potential health hazards and create plans to avoid forward and back contamination and to maintain the scientific integrity of samples relative to specific categories of investigation.

Impact of robotic recon

Robotic recon can potentially provide many benefits. Many of these are readily apparent, but others need to be quantified (through lab and field testing) in order to fully understand their impact and whether they provide a net increase in exploration efficiency and productivity.

Assesses feasibility. Scouting a site prior to crew arrival can help evaluate trafficability; find efficient and interesting routes to potentially important localities; and assess the value of a proposed traverse station. Routes can be surveyed either by following a proposed traverse and evaluating it at points along the way, or by making observations of traverse areas from another perspective (e.g. looking at a crater or rille descent route from the opposite side).

Aids prioritization of sites and tasks. During Apollo 17 EVA #2, Harrison Schmitt discovered orange glass at Shorty Crater. This was one of the most significant finds during Apollo and was *not* visible in remote sensing data. But the EVA plan and walk-back constraints meant that Schmitt had limited time for field investigation. Had the presence of these deposits been known beforehand, more time would have been allocated at Shorty Crater. Alternatively, the site might have been visited earlier in the EVA, or a follow-up visit for additional observations and sample collection could have been considered.

Supplements and complements remote sensing. Resolution fundamentally limits remote sensing in viewpoint and measurement types. Surface based robotic recon can provide ground truth for those things that are visible through remote sensing and provide different and higher resolution data. The oblique, ground-based view is also significant, especially for assessing geologic contacts, working out contextual relationships, and determining the source of boulders at the base of mountains.

Increases understanding of remote sensing data. Surface data can help identify and resolve features that are difficult to discern in remote sensing data. In our November 2008 test, it was pointed out that "Differences in the material on the rim of the crater were not detectable in the satellite image". Moreover, once a feature has been examined with both remote sensing and surface data, that knowledge can be applied to other similar cases. In our Moses Lake field test, for example, we were able to use observations made at one site to design EVA tasks at other sites that we expected to be similar.

Improves Situational Awareness: A key benefit of robotic scouting is increased situational awareness. In particular, scouting data can help prepare crews to know what to look for and what to look at. As a result, EVA tasks (e.g., observations) can be performed faster and more efficiently with procedures worked out beforehand. In brief, robotic recon probably can help a crew prepare to work in a more efficient manner.

Increases EVA Productivity. Experience in space has shown that crew time is always a highly scarce resource, even for long-duration missions. Thus, anything that improves crew productivity (e.g., reducing time on task and increasing quality of results) is extremely important and beneficial. Robotic recon does this by: (1) helping optimize traverse plans (timelines, priorities, etc.) and (2) informing the crew of what to expect at a particular site.

Useful in crew training. Robotic recon can help train and prepare crew for EVA science tasks. In our November 2008 test, one test subject commented, "My [EVA] efficiency would have been greatly diminished if I had not been part of the science operations." During Apollo, crews were part of the planning process; they met at night almost every other day, going through the EVA plan and revising it as appropriate to planning interactions. We believe that having crews take part in recon operations improves their understanding of sites and the work to be performed at those sites.

Improves science return and likelihood of success. According to Mark Helper, a field geologist "often will spend much time stumbling around looking for the one key thing (observation or sample) that puts it all together." This requires that you "cover as much ground as possible" and that you "can't be sure ahead of time what particular observations or samples will be the key". Thus, the more information you have before you start, the greater your chances of finding "the one thing that makes it all fall into place." Robotic lead scouting can assist in identifying where those key observations might be made.

Uses robotics effectively. The current state-of-the-art in planetary robotics makes robotic lead scouting a feasible possibility. Harrison Schmitt has said, "I am still a skeptic on real time integration of crewed EVA and robotic activity. In terms of efficiency, it is distracting, to both. Separating them, as we did [during our November 2008 test], so that robotic activity supports the EVA planning process, makes sense. Real-time interaction may not."

Can happen at a slower pace. Significant time is available for robotic recon. Even if a crew roving vehicle is used in an unmanned mode, it is likely to move more slowly than when the crew is onboard simply due to operational communication issues and the risks of teleoperation. With significantly more time available without crew on the lunar surface, robotic recon does not need to happen quickly in order to be potentially cost-effective.

Does not need to determine everything. Robotic recon is *not* the same as robotic exploration. Whereas robot explorers (e.g., MER) are primary science tools (i.e., used to acquire source measurements), the purpose of recon is to evaluate targets, stations, or sites, for subsequent EVA observations and sampling. Robotic recon does not, therefore, need to maximize science return *by itself*. Instead, recon can focus on *preliminary* assessment.

Does not need to make all the measurements. Robotic recon can provide valuable data even with a limited instrument suite. This minimizes mass, power, cost, and operational requirements. Moreover, the robot also does not need to do all tasks. Humans can sample more intelligently than a robot, given the same information, but a recon robot can provide significant documentation support so that the crew can collect samples efficiently and the recon data will provide additional context for the samples collected.

Does not need to visit the exact route. Robotic recon does not need to drive the same route as planned for crew in order to provide important information for planning and assessment. For example, Figure 4 shows traverse plans that we developed for a hypothetical mission to Hadley Rille [Bro08]. The surface scenario includes robotic recon (stations A to L) crossing Hadley Rille to the East rim, in order to point instruments back toward the West side and assess an EVA descent and traverse into the rille (stations 1 to 6).

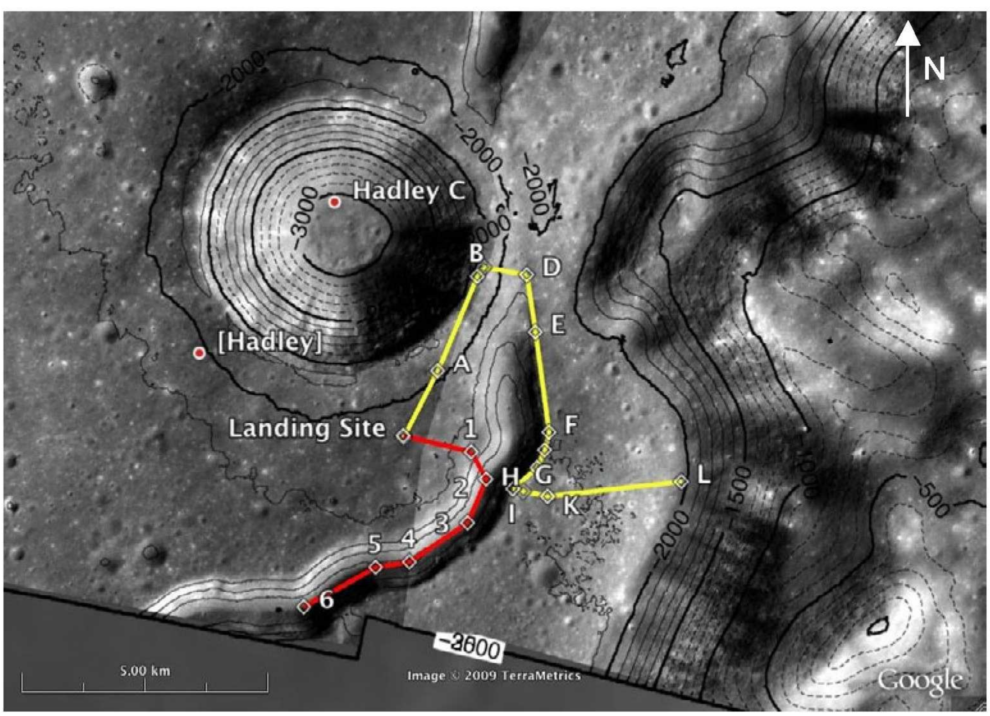

Figure 4. *Hadley Rille traverses: crew (red, stations 1 to 6) and robotic recon (yellow, stations A to L). Robotic recon follows a different route in order to obtain a better view of the crew route.*

Open issues

The concept of robotic recon is simple: *the more information you have, the better you can plan*. As with most human activity, the more you know in advance, the more effective and productive you can be when you start to work. But several important questions remain:

What is the quantitative impact on EVA productivity? How productive are crew EVAs designed using information from robotic scouting, relative to similar EVAs designed without surface data? This also requires appropriate metrics for scientific productivity. Some simplistic quantitative metrics, such as the number of samples collected, or cumulative EVA minutes, will not get at the critical difference. However, it might be possible to assess the overall quality of a map produced by one technique versus the other in a trade study.

What is the operations concept for lunar robots? How do the capabilities and operations of robotic rovers need to be changed from current practice ("robot as science tool") to be used for recon ("robot as scout")? What ground control structure is needed to adequately support the range of plausible scouting activities? How much time and resources does planning and implementing robotic scouting require?

What surface mobility system should be used for scouting? The roving vehicle for astronaut crew mobility could be used in an unmanned mode. However, this presents a risk tradeoff: buying down risk through increased understanding of the site prior to crew activity, at the risk of possibly losing the rover before crew arrive. This is an even greater risk with architectures that use the crew rover as the habitat. Smaller robots could be used instead, but they may not have sufficient power for long-range operations.

What are the required relationships between crew and scouting mobility? This question is motivated primarily by requirements for mobility and speed. In particular, the recon robot does not need to visit the exact traverse route (i.e. observing the descent route from across a crater or rille) to be helpful, so terrainability may not need to be comparable. And there is significantly greater time for scouting prior to (or between) crews. Thus, ground speed may also not need to be comparable.

How should recon data be processed and presented? The design of tools, displays, and protocols all impact the efficiency of science operations. Given that our recent work has identified that analysis, decision making, and plan generation by the science team is the slowest part of the recon process, a key question is: How can we reduce the bottleneck of presenting, viewing, and analyzing recon data?

How should data be logged and georeferenced? What should we use for coordinates, reference frames, and positioning? Sharing position information between different surface assets (e.g., between humans and robots) requires high resolution positioning, as well as fixed references, at work sites. Terrain relative navigation may work for individual visits to unique sites, but if a sample is identified and documented during robotic recon, a later crew will need to be able to find the exact same spot to collect it.

What is the most effective way to coordinate human-robot activity? How should robotic recon data be incorporated into the planning (or replanning) of a crew traverse or an EVA? What scouting data need to be presented to crews in training and during a mission? How and when should this data be conveyed or made available?

Recommendations

Given the potential of robotic recon to significantly improve how humans explore the lunar surface, we recommend that further study be performed so as to support the design and development of lunar EMUs, SPRs, EVA equipment, training plans, and mission control systems. In particular, we recommend that research and development focus on the following objectives:

- Identify and quantify operational requirements for robotic recon in advance of human activity. Emphasis should be placed on supporting high priority science goals as identified by the NAC and NRC.
- Identify and quantify ground control and science team requirements for robotic recon.
- Identify capability, procedure, and training requirements for human explorers to draw maximum benefit from robotic recon during vehicular traverses and on-foot EVAs.

In addition, we recommend that the following key issues be addressed:

Determine how to optimize recon for field exploration. The introduction of robotic activity prior to human fieldwork is a potentially powerful technique for lunar and Martian field exploration. Several important questions are: How do we adapt robotic recon to specific site, science and task needs? What is an optimal scouting instrument package? How much surface science should be performed with the robot *vs.* done by humans? How does geophysical sensing enter the planning sequence?

Determine how to optimize science operations during recon. In our work to date, we have found that science analysis and planning is the central bottleneck in recon operations. In contrast to Mars, lunar surface operations can be significantly more interactive and can involve multiple command cycles per day. Thus, finding ways to make science operations rapid and efficient is of critical importance to both lunar productivity and "Mars forward" applications.

Quantify impact of robotic scouting on EVA productivity. Our studies indicate that recon can be highly beneficial to crew, improving preparation, situational awareness, and productivity. In order to understand how to best integrate recon into lunar architecture, mission design, and training, we need to quantify these benefits. Assessment should thus focus on empirical measures including performance, efficiency, and reliability as well as qualitative evaluation by experienced field explorationists.

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