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Assessment of robotic recon for human exploration of the Moon ☆

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ABSTRACT

Robotic reconnaissance (''recon'') has the potential to significantly improve scientific and technical return from lunar surface exploration. In particular, robotic recon can be used to improve traverse planning, reduce operational risk, and increase crew productivity. To study how robotic recon can benefit human exploration, we recently conducted a field experiment at Black Point Lava Flow (BPLF), Arizona. In our experiment, a simulated ground control team at NASA Ames teleoperated a planetary rover to scout geology traverses at BPLF. The recon data were then used to plan revised traverses. Two-man crews subsequently performed both types of traverses using the NASA ''Lunar Electric Rover'' (LER) and simulated extra-vehicular activity (EVA) suits. This paper describes the design of our experiment, presents our results, and discusses directions for future research.

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1. Introduction

The planned human return to the Moon offers new opportunities to advance the scientific exploration of the lunar surface. However, when the new exploration campaign begins, short human missions (lasting a few weeks) will be separated by several months, during which time robots could perform work [1]. A central challenge, therefore, is to coordinate human and robotic activities to maximize scientific return. We believe that one way to do this is with *robotic recon*.

We define robotic recon as ''remotely operating a planetary rover to scout planned sorties prior to EVA''. Scouting is an essential phase of field work, particularly for geology. Robot instruments can provide observations of the surface and subsurface geology at resolutions and from viewpoints not achievable from orbit. This surface-level data can then be used to improve planning and crew performance.

As a practical example of how such recon would be extremely useful for lunar exploration, we need look no further back than the last human mission to the Moon. During Apollo 17's second EVA, the crew drove from the landing site to the South Massif, then worked their way back. At Shorty Crater (Fig. 1), Harrison Schmitt discovered orange volcanic glass—perhaps the most important discovery of the mission. However, time at the site was severely limited by walk-back constraints (based on consumables). Had the presence of orange glass,

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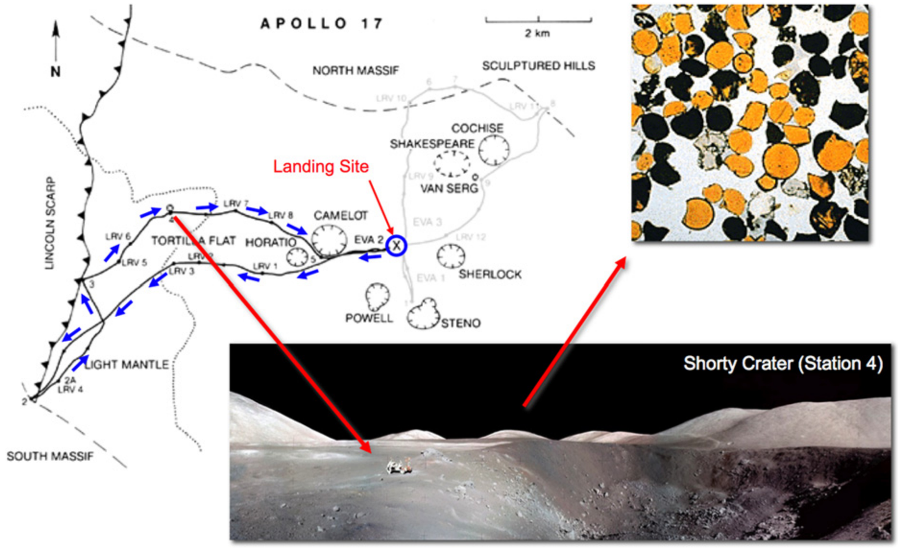

Fig. 1. Orange glass was discovered at Shorty Crater during Apollo 17. Robotic recon could have enabled the crew to spend more time exploring this key discovery by improving traverse planning.

or other pyroclastics, been identified in advance through surface recon, the EVA could have been planned with less time at preceding stations, so that more time could have been spent at Shorty Crater.

Since 2008, we have been developing and evaluating systems, operational concepts, and protocols for robotic recon [2,3]. Our approach is inspired by the Mars Exploration Rovers (MER), as well as human spaceflight, including Apollo, the Space Shuttle, and the International Space Station (ISS). Our ground control, for example, integrates a science team based on both the MER Science Operations Working Group (SOWG) [4] and the Apollo "Science Backroom" [5].

We hypothesize that robotic recon improves human exploration in three ways: (1) it increases scientific understanding so that better traverse plans can be produced, (2) it reduces operational risk by evaluating routes and terrain hazards, and (3) it improves crew productivity by facilitating situational awareness. To test these hypotheses, we conducted a field experiment of robotic recon at Black Point Lava Flow (BPLF), Arizona, during Summer 2009.

In our experiment, we employed a crossover design in which field geology traverses were planned and executed with, and without, robotic recon data. Initially, two "pre-recon" traverse routes were planned using orbital images. We then remotely operated a planetary rover equipped with cameras and 3D lidar to scout the traverses. The recon data were subsequently used to develop "post-recon" traverse plans. Finally, the four traverses (pre- and post-recon in two different areas) were executed by two-man crews using the NASA "Lunar Electric Rover" (LER) and simulated EVA suits. We used several metrics (described below) to assess the impact of robotic recon.

2. Experimental design

We designed our experiment to study: (1) to what extent robotic recon can reduce uncertainty and improve traverse planning prior to human field work and (2) how scouting in advance of human missions can improve crew efficiency and quality of data collection. The experiment involved four phases of activity, which simulated a human–robot exploration campaign.

Initial traverse planning: During the initial phase, a science team developed "pre-recon" crew traverse plans for geologic exploration of the BPLF site using only orbital imagery and "general knowledge" of the region (i.e., what is known about geologic processes and features of the area and at similar sites). The team then identified high priority areas where surface-level observations would help reduce planning uncertainties and developed robotic recon traverses.

Robotic recon mission simulation: In the second phase, we teleoperated a planetary rover to perform recon. A simulated ground control team remotely operated the robot from NASA Ames. The mission simulation included an operational timeline inspired by the MER SOWG and a hybrid operations protocol derived from MER and human spaceflight missions.

Post-recon planning: After the robotic recon mission was complete, the science team created "post-recon" crew traverse plans by modifying the "pre-recon" crew traverses using the recon data. Only details about the site that were contained in the robot data were factored into the traverse replanning.

Crew mission simulation: The final phase involved execution of the "pre-recon" and "post-recon" traverses by crews using the LER and simulated EVA suits. Two crews each performed one traverse with the benefit of recon information and another traverse without. A "science backroom" remotely supported the crews.

2.1. Definitions

The following are shown in Fig. 2:

EVA station—a location where crew performs an EVA,

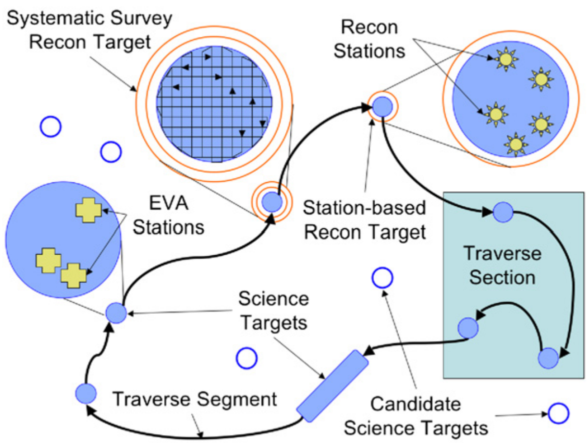

Fig. 2. Traverse definitions.

*recon station*a—a location where a robotic rover deploys instruments, collects data, or leaves a marker,
science target—a point feature (e.g. a boulder), a linear feature (e.g., escarpment), or a bounded area,
candidate science target—a science target that may be added to a traverse plan,
recon target—a science target or candidate science target that is selected for recon,
station-based recon target—a recon target where the robot collects data at one (or more) recon stations,
systematic survey recon target—a recon target where the robot is used to collect dense survey measurements,
traverse segment—a translation portion of a traverse,
traverse section—a portion of a traverse that may include multiple targets and segments.

2.2. Assumptions

- The pre-recon traverse plans were developed using only lunar-relevant remote sensing data and general knowledge of the region.
- Science team members had not previously performed field work at the site.
- Previous missions to the region had collected samples, but not yet been analyzed.

2.3. Ground rules

- Orbital imagery used for planning did not exceed Lunar Reconnaissance Orbiter (LRO) resolution.
- The science team did not use knowledge of what was seen by crew and science backrooms during previous missions, including prior surface-level data.
- Only data available before and from recon were used for planning and revising the traverses.
- The same science team created both the pre- and post-recon traverse plans.
- Serendipitous discoveries were not considered when assessing metrics.
- Recon for any given target reflected a ratio of 14-day crew mission to 6-month robotic mission.

2.4. Black Point Lava Flow

Black Point Lava Flow (BPLF) is located 65 km north of Flagstaff, Arizona. It was selected by the NASA Desert Research and Technology Studies (D-RATS) project as a lunar analog test site for its geologically relevant features, including outcrops of basaltic rocks and unit contacts. The size of the test area ($\sim$3,000 km^2) and abundance of geologic features enable extended range simulated science sorties [6].

2.5. Science objectives

D-RATS defined a set of science objectives for lunar mission simulations. The primary objective is to *determine the origin, nature, and relative ages of the geologic units to determine the geologic history of the site*. The secondary objectives are:

- characterize the BPLF, in particular its age, morphology, structure, petrology, mineralogy, etc;
- determine the relationship of BPLF to other lava flows and volcanic features;
- characterize the other geologic units and their relation to the BPLF in space and time; and
- determine the geologic history of the site and determine the ages to the major units as possible;
  We used these notional objectives as guidelines for traverse planning and execution in our experiment.

3. Effect on traverse planning

We expected that robotic recon would improve traverse planning by reducing scientific and operational uncertainties (route selection, trafficability, etc.). For example, robotic recon should enable more precise targeting of accessible locations that are likely to yield higher science return. To study this, we developed three hypotheses to evaluate the effect of robotic recon on traverse planning (Table 1).

3.1. Science potential (Hypothesis 1A)

To test the hypothesis that "robotic recon can improve the science potential of a traverse plan", we employed a "science potential" rating scale (Table 2). This metric estimates how well a target may *help* address exploration science objectives. A target that is *believed* to facilitate acquiring key observations, samples, etc. will have a better rating than a target that does not.

Table 1
Traverse planning hypotheses.

#	Hypothesis
1A	Robotic recon can improve the science potential of a traverse plan
1B	Robotic recon can substantially change the design of a traverse plan
1C	Robotic recon can reduce the science uncertainty in a traverse plan

To evaluate science potential, we asked the science team to rate science targets on the pre- and post-recon traverses prior to the crew mission simulation. We also asked geologists to ground truth for each station. To test the hypothesis, we will compare all the ratings.

3.2. Qualitative change (Hypothesis 1B)

To test the hypothesis that "robotic recon can substantially change the design of a traverse plan", we employed a "qualitative change" rating scale (Table 3). This metric assesses the extent to which targets change *based on* recon. The metric considers four factors: location, objectives, activities, and priority.

To evaluate qualitative change, the science team assessed each factor and then combined all the factors to obtain a single rating for each target. Depending on the nature of a particular target, factors may not be equally weighted when combined. Adding a new target, or deleting an existing one, is a complete change.

3.3. Uncertainty (Hypothesis 1C)

To test the hypothesis that "robotic recon can reduce the science uncertainty in a traverse plan", we employed the "certainty" rating scale shown in Table 4.

To evaluate uncertainty, we asked the science team to rate science targets on both the pre- and post-recon traverses prior to the crew mission simulation.

4. Effect on crew productivity

We expected that robotic recon would improve crew productivity by enabling execution of planned field work to be more efficient. In particular, recon data should enable tasks to be performed better and with reduced overhead. To study this, we developed two hypotheses to evaluate the effect of robotic recon on crew productivity (Table 5).

Table 2
Science potential rating scale.

Rating	Definition
Poor	Limited potential to address science objectives
Fair	Some potential to confirm existing hypotheses and facts
Good	Good potential to elucidate existing hypotheses in detail
Very good	Likely will help address scientific objectives or identify new questions
Excellent	Significant opportunity to resolve scientific questions

4.1. Crew productivity (Hypothesis 2A)

To test the hypothesis that "robotic recon can improve the productivity of a traverse", we used the "Weighted Sum of Completed Traverse Objectives" (WSCTO) [7]. This metric is based on the Pavilion Lakes Research Project "Scales of Science Merit and Data Quality" [7], but is applied to individual targets.

We characterized data quality using two types of criteria: (1) quantitative, such as signal-to-noise ratio and statistical significance and (2) qualitative, such as the value of the data from a scientific impact (discovery or confirmation) standpoint.

In this experiment, we assessed WSCTO as

$$\mathrm{WSCTO} = \sum \mathrm{VT}(n) \times \mathrm{DQ}(n) \tag{1}$$

where $\mathrm{VT}(n)$ is the "value of target n" (Table 6) and $\mathrm{DQ}(n)$ the "Quality of data collected at target n" (Table 7). The linear sum is designed to enable absolute comparison of the productivity of different traverses in the same region.

Table 4
Certainty rating scale.

Rating	Definition
Dubious	$<5\%$ certain, high possibility for error, little is known about site
Unclear	$<25\%$ certain
Toss-up	50% certain, could go either way
Confident	$>75\%$ certain
Indisputable	$>95\%$ certain, little doubt, low ambiguity

Table 5
Crew productivity hypotheses.

#	Hypothesis
2A	Robotic recon can improve the productivity of a traverse
2B	Robotic recon can improve the efficiency of performing a traverse

Table 6
Weighted Sum of Completed Traverse Objectives (WSCTO) value of target scale.

Value	Definition
1	Low anticipated importance
2	Moderate anticipated importance
3	High anticipated importance

Table 3
Qualitative change rating scale.

Rating	Location change	Objectives change	Activities change	Priority change
Insignificant	No change	Little/no change	Little/no change	No change
Small	<10 m	Changed some objectives	Changed some activities	Changed by ± 1
Medium	<50 m (half EVA range)	Changed half of objectives	Changed half of activities	Changed by ± 2
Large	<100 m (EVA range)	Changed most objectives	Changed most activities	Changed by ± 3
Complete	>100 m	Changed all the objectives	Changed all the activities	Changed by ± 4

Table 7
Weighted Sum of Completed Traverse Objectives (WSCTO) data quality scale.

Data Quality	Definition
1 No data	No data or relevant observations
2 Limited	Video and navigation did not support scientific observations
3 Adequate	Quantitative data adequate for general documentation of findings. Provides useful context and enables efficient return. Data is marginally publishable
4 Significant	Quantitative data adequate to support documentation of scientific findings and yielding publishable results
5 Exceptional	High quality video, navigation, and other quantitative data that supports and enhances scientific merit

4.2. *Crew efficiency (Hypothesis 2B)*

To test the hypothesis that "robotic recon can improve the efficiency of performing a traverse", we assessed the "percent of time on task" (PTT). PTT is indicative of how much time crew is able to work on a task (e.g., field geology) vs. performing non-productive activities. Non-productive activities include crew idle time, navigating, negotiating terrain and obstacles, locating specific features of interest, etc.

We expect that surface-level data acquired by robotic recon improve the crew's preparedness and facilitate their situational awareness. Thus, the PTT should be higher for traverses planned with recon data.

5. Initial traverse planning

Prior to the robotic recon mission, we convened a science team to review the BPLF science objectives, decide on allowable *a priori* data (satellite imagery, geologic maps, etc.), organize and assign responsibilities within the science team, and develop traverse plans (both crew and robotic recon). We assigned traverse leads (i.e., principal investigators) to two areas of the BPLF, the "West" and "North" zones (Fig. 3).

5.1. *Traverse planning*

The West and North traverse leads developed two one-day "pre-recon" crew traverses, W1 and N1, using only satellite data and limited knowledge about the site. Satellite data included 60 cm/pixel, panchromatic QuickBird imagery and 15–90 m/pixel advanced spaceborne thermal emission and reflection radiometer (ASTER) imagery. ASTER provides 14 spectral bands ranging from visible to thermal infrared, which help assess surface composition.

Fig. 4 shows the two pre-recon traverses. The pre-recon West traverse, W1, was designed to explore five geologic units in an Apollo-style manner (i.e., rapid area coverage, assumes this is the *only* time the area will be visited, etc). W1 has 15 stations, covers 10.1 km, and is estimated to require 8:58 h to complete (including a total of 6:25 man hr of EVA).

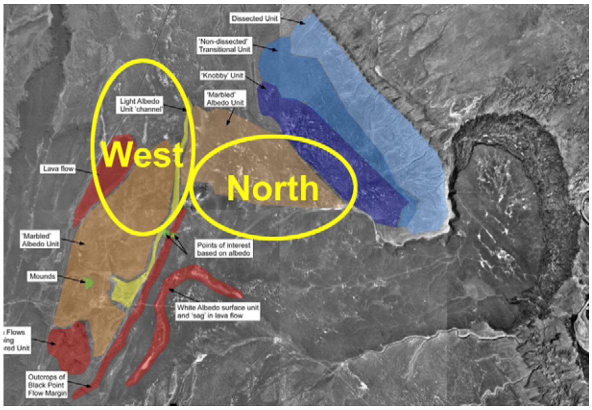

Fig. 3. Geologic map of the BPLF. West and North zones are circled in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

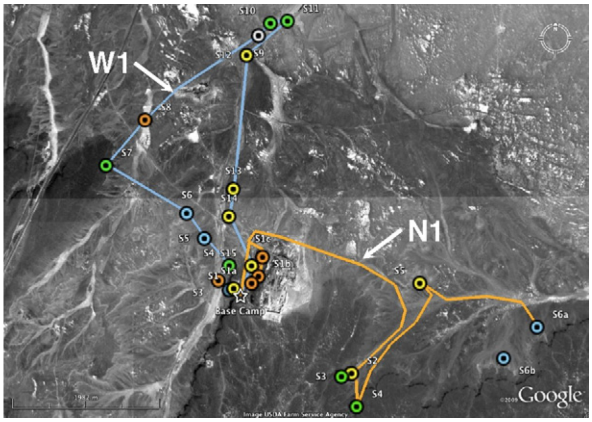

Fig. 4. Pre-recon crew traverses, W1 (blue) and N1 (orange), overlaid on a 60 cm/pixel base map. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The pre-recon North traverse, N1, was designed to characterize the northern edge of the BPLF. The traverse is much less exploratory than W1 and emphasizes sampling the flow edge. N1 has 6 stations, covers 10.6 km, and is estimated to require 8:47 h to complete (including a total of 10:40 man hr of EVA).

6. Robotic recon mission simulation

From 14 to 27 June 2009, we simulated a lunar robotic recon mission. During this test, we used a NASA Ames "K10" robot (Fig. 5) to scout the BPLF. A ground control team remotely operated K10 from the NASA Lunar Science Institute in California.

To perform recon, K10 carried three science instruments (Fig. 6): an Optech ILRIS-3D scanning lidar (provides 3-D topography measurements at 500+ m range); a GigaPan panoramic camera (provides oblique, color images with up to 330° field-of-view and gigapixel

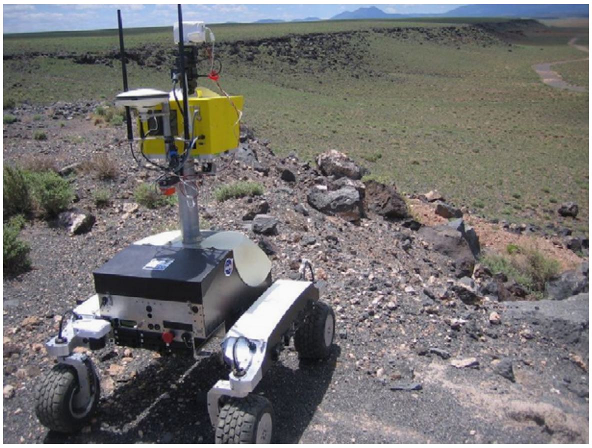

Fig. 5. K10 robot operating at BPLF.

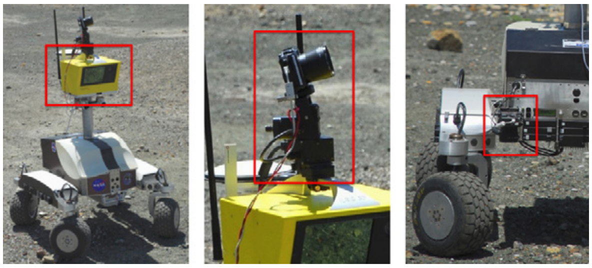

Fig. 6. Left to right: (1) 3D scanning lidar, (2) GigaPan camera, and (3) microscopic imager.

resolution); and a downward-facing microscopic imaging camera (provides color images of terrain surface composition and features at 55 μm/pixel).

We remotely operated K10 using a prototype ground control (Fig. 7) for lunar surface robotics [1,8]. In this ground control, the ''Science Operations Team'' performs analysis and planning like the MER Science Operations Working Group. The ''Flight Control Team'' performs real-time, tactical operations similar to those of human flight missions (Apollo, the Space Shuttle, and the International Space Station) [5].

We used ''Google Earth'' extensively for robot traverse planning and operations [1]. Google Earth is very flexible as a map viewer. It allowed us to display a wide range of geospatial content (image/map overlays, points, etc.) and provided a unified operational view for reviewing site data, robot plans, robot activities, and data collected during recon.

Within W1 and N1, the traverse leads identified high priority areas where more detailed information was needed to better assess the science merit of targets, or to better assess the accessibility or trafficability of a route or target. Fig. 8 shows the recon goals that we developed to scout W1. These focused primarily on reducing the science uncertainty of several targets.

In the North area, the traverse lead identified trafficability of the planned route from station S1c towards the north (Fig. 9, orange line) as a concern and requested that robotic recon acquire panoramic imagery to assess the route.

The science team used Google Earth to develop recon traverse plans by specifying waypoints and data collection activities directly on the map. These traverse plans varied significantly in duration and complexity. After a plan was defined, the flight control team vetted it (to verify operational constraints) and then executed the plan with the robot.

While K10 was operating, we continuously tracked its location in Google Earth (Fig. 10). As K10 acquired recon data, geo-registered placemarks were automatically added to the Google Earth display. Placemarks contained preview images as well as hyperlinks to the K10 ''Ground Data System'', which allowed scientists to work directly with source data.

By the end of recon operations, K10 had acquired more than 8.5 GB of data. (Fig 11) shows an iconic view of all the recon data—95 microscopic terrain images are shown as yellow ''M'' squares, 39 lidar scans are shown as pink ''L'' wedges, and 75GigaPan panoramas are indicated as green ''P'' wedges.

Fig. 12 is a geospatial view of the data collected by K10. As the image shows, we collected recon data from six zones at BPLF, with the majority of the data taken at a central basin area. In total, we performed 52 h of robotic recon, including recon traverse planning, robot operations, and science data analysis. K10 operated for 40 h, of which 15 h was productive time (time acquiring recon data) [9].

7. Post-recon planning

After completion of the robotic recon mission simulation, the science team reviewed the collected data. They then revised the pre-recon traverse plans using the data to reevaluate target science merit, to add/delete stations, to adjust station locations, and to modify crew tasks. The resulting post-recon crew traverses were designated as W2 and N2.

For example, based on recon data, the West science team decided to combine the objectives for W1 Station 2 and W1 Station 4 (Fig. 13). The location of the new station, W2 Station 2, is coincident with the location of W1 Station 4. The rationale for this change was as follows:

- recon indicated that descent from the lava flow surface is better done to the north;
- the geologic relationships at this location are high priority and all objectives originally tasked for W1 Stations 2 and 4 could be done at a single station;
- a single station allows a reduction in EVA activities and time, which makes it easier to keep within the overall traverse time constraints;
- removal of W1 Station 2 saves time in W2;
- consolidation of stations combines a high priority site with a low priority site, which enables multiple objectives to be addressed at a single location.

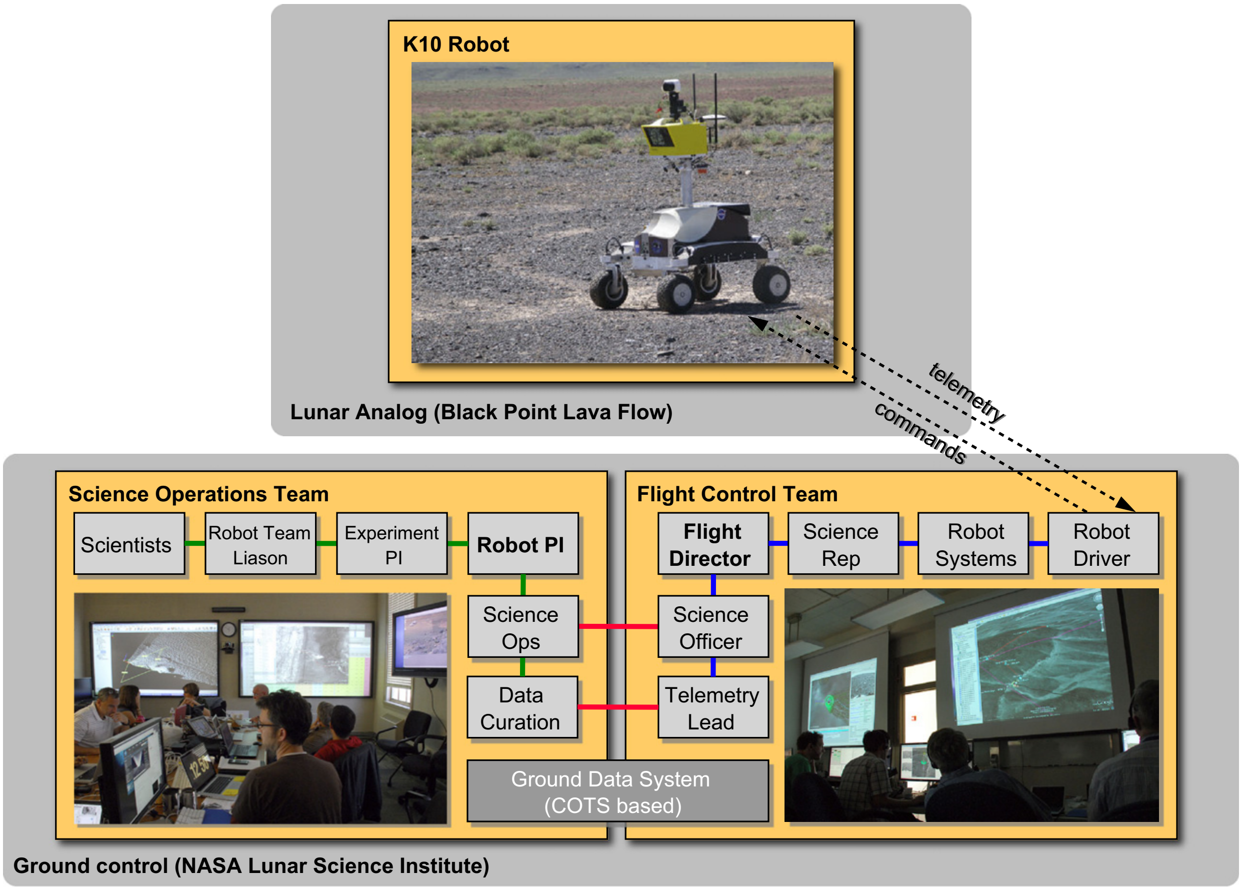

Fig. 7. Prototype ground control for lunar robotics is a hybrid of Apollo, Space Shuttle, Space Station, and MER operational concepts.

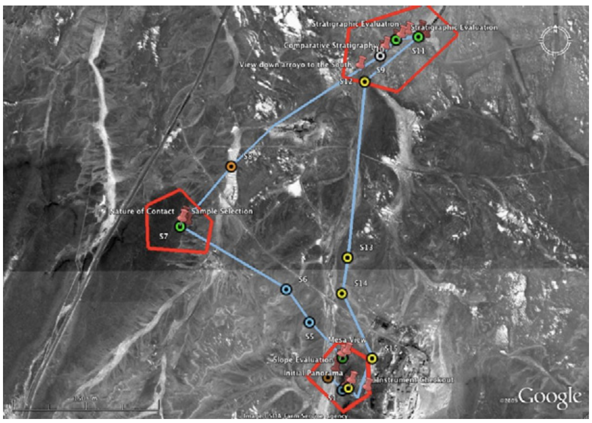

Fig. 8. West recon goals. Traverse stations are colored based on priority (green is the highest) and three zones (red) have been selected for recon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Trafficability of N1 (orange) is a concern north of S1c. Recon (red) addresses this via panoramic images (field-of-view is shown in green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Similarly, at other targets, the science team made adjustments to more efficiently utilize crew EVA time. Surface features and operational issues that were not detectable from satellite imagery, but that were observable in the recon data, influenced the replanning.

8. Crew mission simulation

We conducted the final phase of the experiment from 29 August to 3 September 2009 as part of the 2009

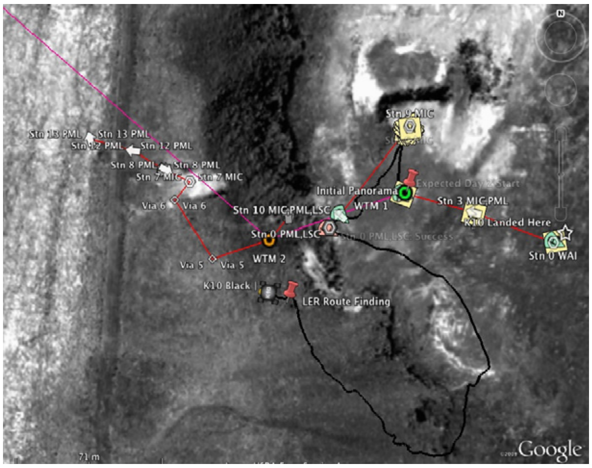

Fig. 10. K10 path (black) and geo-located data display (icons) shown in Google Earth.

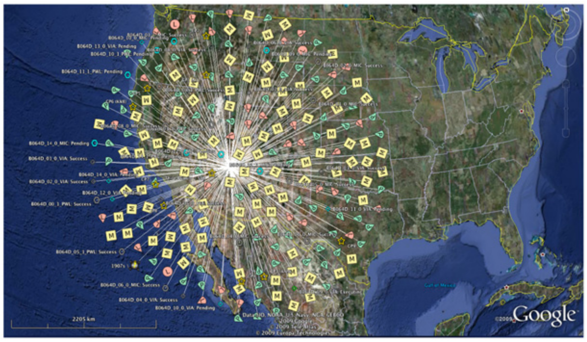

Fig. 11. Iconic view of all robotic recon data collected by K10 at BPLF. Each icon represents an individual piece of data collected with a particular instrument (imager, lidar, etc.)

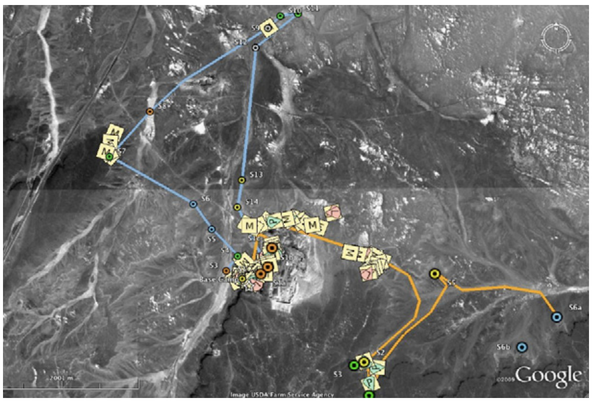

Fig. 12. K10 collected recon data from six zones at BPLF. The two "pre-recon" crew traverses are shown in blue (W1) and orange (N1). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

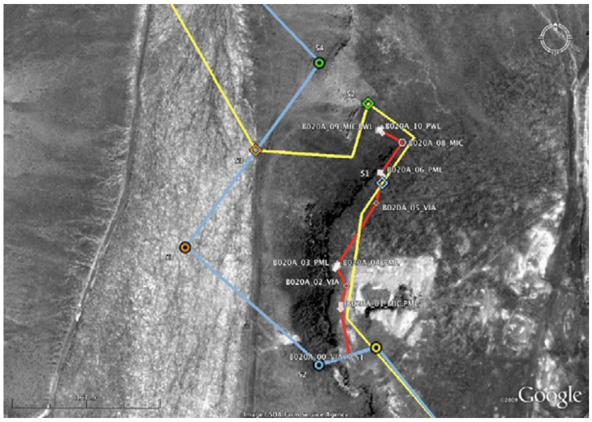

Fig. 13. Portions of traverses W1 (blue) and W2 (yellow). K10 recon plan #B020A is shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

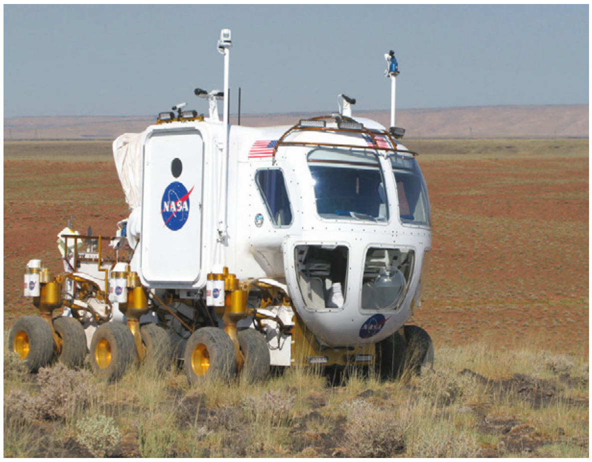

Fig. 14. Lunar Electric Rover at BPLF.

D-RATS field test at BPLF. During D-RATS, two crews each performed two single-day traverses (one pre-recon and one post-recon) using the "Lunar Electric Rover" (LER) and simulated EVA suits. Each crew consisted of an astronaut and a field geologist.

The LER (Fig. 14) is a prototype pressurized crew rover that is intended to improve human safety and performance in planetary exploration [7]. The LER is slightly larger than the Apollo Lunar Roving Vehicle and provides a pressurized shirt-sleeve environment, along with two "suit ports" for rapid egress and ingress. The LER is equipped with numerous cameras, which provide multiple video channels to ground control. A mast-mounted GigaPan camera can be remotely operated to acquire high-resolution panoramas.

A ground control team (Fig. 15) remotely supported the crew throughout the traverses. In this ground control, a "Science Backroom" provided real-time, interactive support to the crew via a voice loop. This backroom operates in a manner similar to the "Science Backroom" used during Apollo, but includes a "SCICOM" operator, who is able to communicate directly with the crew.

The ground control also included an "ops team", which is a simplified flight control team. The ops team performed

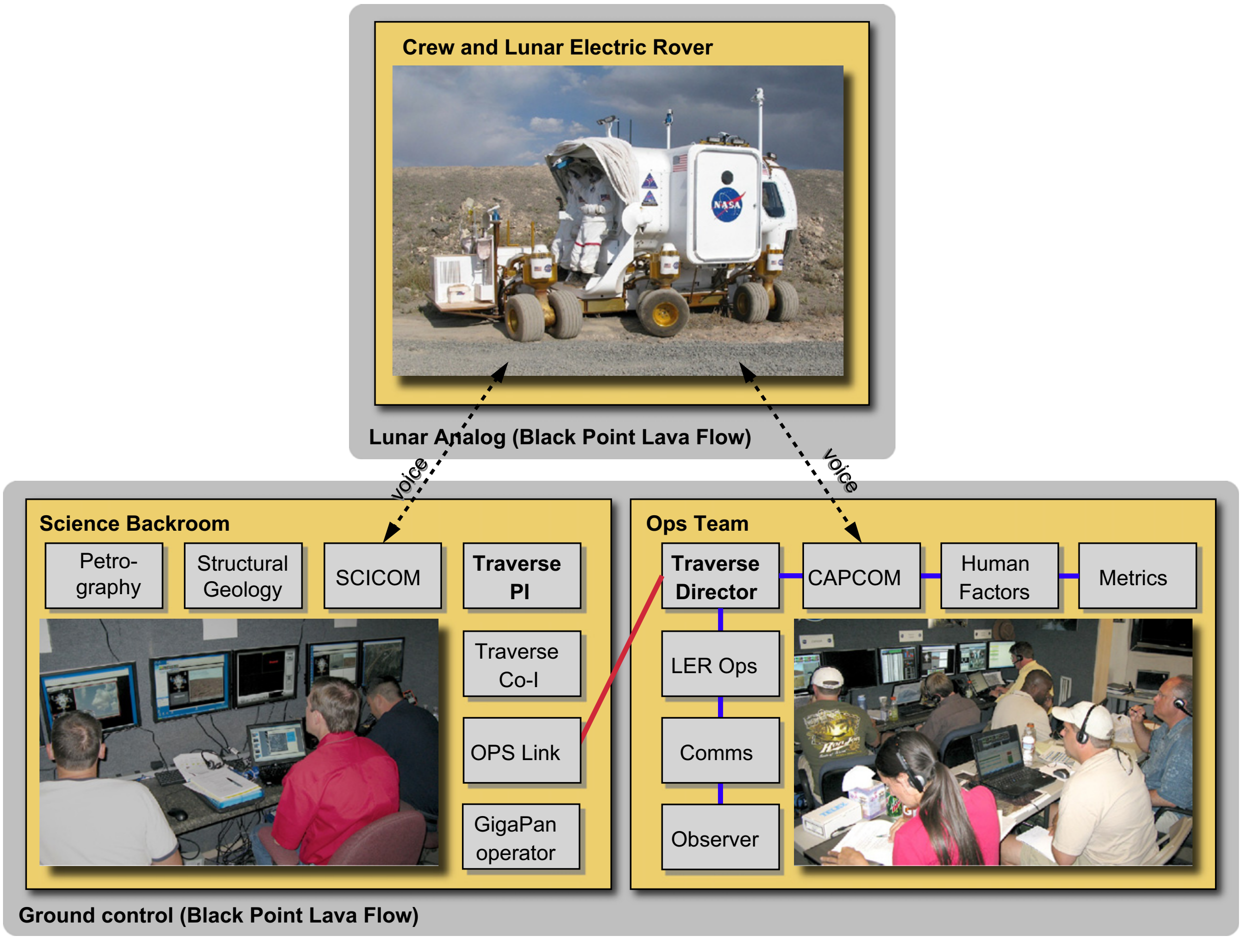

Fig. 15. Prototype ground control for lunar crew mission with the LER. Both the "ops team" (simplified flight control) and the "science backroom" are able to talk with the crew.

real-time tactical support, with an emphasis on providing guidance and tracking to a nominal timeline for each traverse plan. As with human flight missions, this team includes a "CAPCOM" operator, who is the designated ops person, responsible for communicating with the crew (in coordination with "SCICOM"). The "Traverse Director" coordinates activities of the Science Backroom with the "OPS Link" position.

Numerous factors impact the performance of field geology with a pressurized rover and EVA suits. These include, but are not limited to:

- crew training, experience, and skill (vehicle, suits, and ops protocols);
- ground control training, experience, and skill;
- group dynamics (teamwork, communication, etc.);
- trafficability (topography, soil conditions, etc.);
- communications (coverage, bandwidth, etc.);
- vehicle problems (mechanical, avionics, etc.);
- environmental conditions (weather, temperature, illumination, etc.);
- site knowledge (prior visits, reports, etc.).

Each of these factors can be difficult (or impossible) to control during a field test, especially if test time is limited, or if it is impractical to conduct a significant number of trials.

For the purposes of this experiment, therefore, we chose to control a single variable—use of recon data. Specifically, we ordered traverses such that each crew performed a pre-recon traverse followed by a post-recon traverse. Thus, the first crew performed N1 then W2; the second crew performed W1 then N2.

For the pre-recon traverses (N1 and W1), we provided the crew and the science backroom with briefing books that contained only traverse maps and satellite images. For the post-recon traverses (N2 and W2), we provided briefing books that also contained images acquired by robotic recon. In addition, during execution of N2 and W2, we gave the science backroom interactive access to all the recon data using the K10 "Ground Data System".

As the crews carried out the traverses, we logged task times, assessed the quality of data, and noted anomalies and potentially biasing events (e.g., inadvertent use of recon data during pre-recon traverses). We also had field observers follow crew and collect ground truth at each target.

9. Results

After analyzing all the data collected during the robotic recon experiment, several important points are apparent. We summarize these points below. Most importantly, it is clear that comparing crew traverse plans developed with, and without, robotic recon provides significant insight into the benefit of surface-level data. However, we have found that comparing crew travers*es as executed* is impractical, due to the difficulty of fully controlling external factors.

9.1. Robotic recon mission simulation

During the robotic recon mission simulation, we monitored robot telemetry and computed a variety of performance metrics in real time [9]. These metrics included task timers (to compare expected performance to actual), Work Efficiency Index [10] (ratio of productive to overhead time), and measurement of human–robot interaction.

These metrics provide insight into the efficiency of ground control. For example, to maximize data acquisition, the science operations team tried to minimize robot idle time. Thus, robot idle time is indicative of traverse planning efficiency. On average, the science team was able to generate new plans with 31 min robot idle time (Fig. 16).

We also monitored whether a traverse plan was successfully completed and robot execution time. Over the course of the mission simulation, a total of 37 robot traverse plans were executed. Of these, 17 plans were partially completed, and 20 were fully completed. The large number of partially complete plans reflects: (1) robot performance limitations (i.e., inability to negotiate some parts of the terrain) and (2) the operations approach we used, which allowed plans to be interrupted (and replanned) based on real-time data.

Fig. 17 shows the ratio of actual time on plan to estimated time on plan for the robot traverse plans that went to completion. Of the 20 plans that were completed, 16 plans were completed within 10% of the allocated time.

For lunar recon operations, minimizing all human interaction time may not translate to more efficient recon operations. In fact, it may often be more time and resource efficient to teleoperate the robot in difficult terrain than to operate autonomously. Thus, our objective was to *minimize* the time spent on unplanned human intervention.

We measured the "Mean Time to Intervene" (MTTI) [11] as the average time humans spent handling anomalies that interrupted robot activity. We also computed the

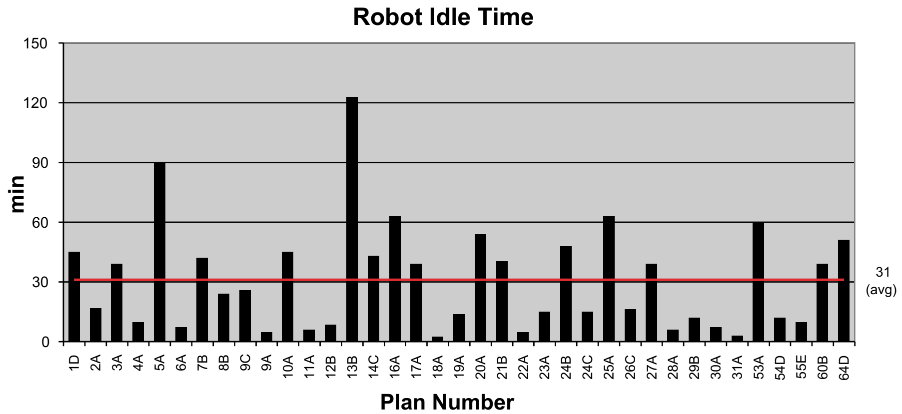

Fig. 16. Robot idle time.

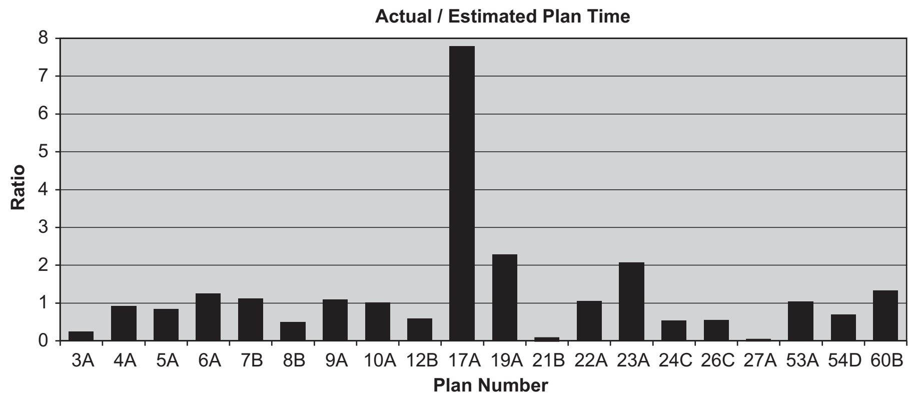

Fig. 17. Ratio of actual plan time to estimated plan time. This ratio equals 1.0 for a plan executed in exactly the expected time.

"Mean Time Between Interventions" (MTBI) [11] as the average time between unplanned interventions. Small MTTI and large MTBI indicate good human–robot performance. The average MTTI for the recon mission was 5.6 min, ranging from a minimum of 1.6 min to a maximum of 17.9 min. MTBI averaged 24 min and ranged from 5.5 min to 1 h [9].

9.2. Crew mission simulation

In our crew mission simulation, robotic recon was of major benefit to the West region, because the pre-recon traverse (W1) emphasized rapid area coverage and visited several different, widely separated geologic units. From a planning standpoint, this meant that there was a large set of unknowns that recon helped resolve, in terms of target access (trafficability, route, approach direction) and science priorities. Table 8 details the qualitative change between the pre-recon (W1) and post-recon (W2) traverses. As the table shows, a majority of the stations were significantly changed based on robotic recon.

In addition, because EVAs were potentially numerous in the West, recon information was essential for prioritizing LER and EVA targets. This was especially true during the W2 traverse, when the science backroom was required to make real-time replanning decisions to accommodate time constraints and changing priorities. In other words, recon enabled the crew and science backroom to be more flexible and adaptive during W2, which enabled all the high priority science objectives to be achieved even under difficult field conditions.

Robotic recon was of less benefit to the North region, primarily because the pre-recon traverse (N1) had a narrower scientific objective, i.e., characterize the BPLF and its contact with the underlying geologic unit. In addition, the recon instruments carried by K10 had limited capability to address this objective. If K10 had been equipped with additional instruments (e.g., spectrometers), recon could have focused on identifying and classifying candidate targets for sampling.

Consequently, the N1 traverse had fewer scientific uncertainties that could be resolved by the robotic recon than the W1 traverses. As a direct result, the northern recon focused primarily on reducing operational unknowns—verifying that the planned route and waypoints were trafficable for the LER (in terms of slopes, obstacles, etc.), identifying and improving precise locations for LER stops (including approach and departure directions), etc. Table 9 details the qualitative change between the pre-recon (N1) and post-recon (N2) traverses. As the table shows, only two stations were significantly changed based on robotic recon.

After all the traverses were complete, we interviewed the crew and asked what recon information would be the

Table 8
Qualitative change between pre-recon (W1) and post-recon (W2) traverses. Shaded cells indicate stations that were significantly changed due to robotic recon.

W1 station	W2 station	Change	Rationale	Qualitative Change Rating
1	**1**	location moved closer to edge	recon determined a better location, which was more 100m	**Complete**
2		deleted (objectives moved to W2 station 4)	recon determined that the stationtion could be deleted	**Complete**
4	**2**	objectives of W1 station 2 and W1 station 4 combined @ location of W2 station 4	location did not change, but more than half the activities changed	**Medium**
3	**3**	location moved north	station was moved by $>$ 100 m but the move was not justified by recon information (no recon conducted)	Insignificant
5	**4**	changed to waypoint (eliminated EVA. Now just drive by & comment)	changed to waypoint, eliminated EVA, now just drive by and comment	**Large**
6	**5**	changed to waypoint (eliminated EVA. Now just drive by & comment)	changed to waypoint, eliminated EVA, now just drive by and comment	**Large**
7	**6**	location moved up slope	moved location by 30 m, division of labor into separate EVA activities based on recon	**Large**
	6a	NEW	study feature identified during recon	**Complete**
	6b	NEW	study feature identified during recon	**Complete**
–	**6c**	NEW	study feature identified during recon	**Complete**
	6d	NEW	study feature identified during recon	**Complete**
	6e	NEW	study feature identified during recon	**Complete**
8	**7**	NO CHANGE	limited recon data collected but not analyzed	Insignificant
9	**8**	objectives of W1 station 9 and station 10 combined at a midpoint, activity for EVA 1 added	70+m change in location, activities from 2 stationtions merged into 1 stationtion	**Complete**
10		objectives of W1 station 9 and station 10 combined at a midpoint, activity for EVA 1 added		
11	**9**	operational change	changes due to modification of traverse plan, but not motivated by recon	Insignificant
12	**10**	NO CHANGE (no recon conducted)	no recon conducted	Insignificant
13	**11**	priority change only	priority changed based on limited recon data	Small
14	**12**	changed to waypoint, no activities	changed to waypoint, eliminated EVA, now just drive by and comment	**Large**
15	**13**	NO CHANGE (no recon conducted)	no recon conducted	Insignificant

Table 9
Qualitative change between pre-recon (N1) and post-recon (N2) traverses. Shaded cells indicate stations that were significantly changed due to robotic recon.

N1 station	N2 station	Change	Rationale	Qualitative Change Rating
1a	**1a**	Was one of three equal options. Recon designated to be prime EVA site.	Recon determined this to be the best cross-section of basalt and the overlying unit	Small
1b		Was one of three equal options. Recon dropped this option completely.	Recon determined that the station could be deleted. This location is > 100 m from 1a, so unreachable if not a designated stop	**Complete**
1c	**1c**	Was one of three equal options. Recon designated to be alternate for 1a.	Recon determined Sta 1a to be the best location, with this location as a backup if crew finds accessibility or rock fall hazard concerns	Small
1 to 2	**1 to 2**	NO CHANGE	Recon verified trafficability of route from Sta 1 to Sta 2	Insignificant
2	**2**	made optional: crew can decide to skip in favor of Sta 3, which K10 identified as same layered unit.	Changed from required to optional (but not deleted); skip option eliminates lower priority objective (sampling channel sediment)	**Large**
3	**3**	–	no recon conducted	Insignificant
4	**4a**	identified that LER might not be able to reach the station (crew might need to park lower on slope)	No change, outcrop location and tasks are the same	Insignificant
—	**4b**	Inserted possible LER stop location to start EVA.	Recon identified that LER might not reach Sta 4a due to trafficability. Might need to park lower on slope at Sta 4b. However, this may have been apparent to crew without recon.	Small
5	**5**	–	no recon conducted	Insignificant
6a	**6a**	–	no recon conducted	Insignificant
6b	**6b**	–	no recon conducted	Insignificant

most useful to have on-board the LER. Their responses fell into two categories: (1) data to improve situational awareness, such as images of navigation and approach/departure landmarks; and (2) guidelines for operations (e.g., surface roughness map) to help LER driving and EVA work (e.g., where and what to sample).

10. Discussion

10.1. Open issues

The concept of robotic recon is simple—the more information you have, the better you can plan. However, several important questions still need to be answered.

What should be 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 instrument") to be used for recon ("robot as scout")? What ground control structure is needed to support scouting activities?

What surface mobility system should be used for scouting? The LER could be used in an unmanned mode. However, this presents a tradeoff—improving understanding of a site prior to crew activity vs. risking damage to the rover before crew arrive. Smaller robots could be used instead, but they may not have sufficient power for long-range operations.

What are the required relationships between crew mobility and recon mobility? In particular, does a recon robot need to have the same performance as a crew rover? Recon may not need to follow the same route as crew (e.g., assessing a descent route into a crater might best be done from an opposing viewpoint), so terrain performance might not need to be the same. Also, there may be significantly greater time for robot missions. Thus, ground speed might 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 analysis, decision making, and plan generation can be slow, a key question is—How can we reduce the bottleneck of viewing and analyzing recon data?

How should recon data be logged and georeferenced? Sharing position information among different exploration assets (humans, robots, orbiters) might require absolute positioning, or fixed references. Terrain relative navigation may work for individual visits, but if a sample is identified during recon, a later crew will need to be able to find the exact spot to collect it.

What is the most effective way to coordinate human—robot activity? How can robotic recon data be most rapidly and effectively 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 there data be conveyed or made available?

10.2. Future work

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

First, we need to determine how to optimize recon for field exploration. The introduction of robotic activity prior to human field work is a potentially powerful technique for planetary exploration. Several important questions are: How do we adapt robotic recon to specific site and science needs? How much recon is needed to significantly enhance astronaut productivity? What instruments are "optimal" for recon?

Second, we need to understand 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 with Mars, lunar surface operations can be significantly more interactive and can involve many command cycles per day. Thus, finding ways to make science operations rapid and efficient is of critical importance to all future planetary exploration.

Finally, we need to conduct additional field testing to further quantify the 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 the design of a multi-mission lunar campaign, we need to more thoroughly quantify these benefits. Assessment should focus on empirical measures, including performance, efficiency, and reliability as well as qualitative evaluation by experienced field geologists.

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