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USING ROBOTS BEFORE AND AFTER HUMANS TO IMPROVE SPACE EXPLORATION

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Human-robotic partnership should not be limited to side-by-side concurrent and coordinated activities. As advanced as robots have become, they are still slow compared to humans. Concurrent, interdependent operations risk creating situations where the human waits for the robot while it is executing or stuck. Robots that cause humans to waste precious resources such as time or life support consumables risk making human missions less productive rather than more. An alternative is to separate human and robotic activities in space and/or time but design and coordinate their activities to be complimentary.

I. INTRODUCTION

In our recent work we have investigated how to utilize robots before or after human missions, in a precursor or follow-up capacity, to benefit the overall effectiveness and return of the combined system.

Robotic recon is a remote robotic operation to scout planned sorties prior to EVA activity. Instruments provide measurements of the surface and subsurface at resolutions and from viewpoints not achievable from orbit. This surface-level data can then be used to inform the planning process and improve situational awareness for operations. In 2009 we conducted a robotic reconnaissance field test at Black Point Lava Flow in Arizona, USA in conjunction with the Desert RATS test. This test gave us new insights on the utility of robotic reconnaissance and design considerations for improving the utility of the approach.

Robotic follow-up is a remote robotic operation subsequent to human excursions which augments the work accomplished by humans. In 2010, we conducted analog field tests with human and robot teams at Haughton Crater on Devon Island, Canada. These experiments focused on two field geology campaigns carried out by simulated EVA crewmembers. This test showed how robotic follow-up can help fill in gaps in knowledge derived from short duration human missions, and on design considerations for improving the utility of robotic follow-up.

In this paper, we discuss the motivation for robotic reconnaissance and robotic follow-up, describe the scientific context and system design for our work, the experimental approach and data we have collected, and present results and lessons learned from field testing.

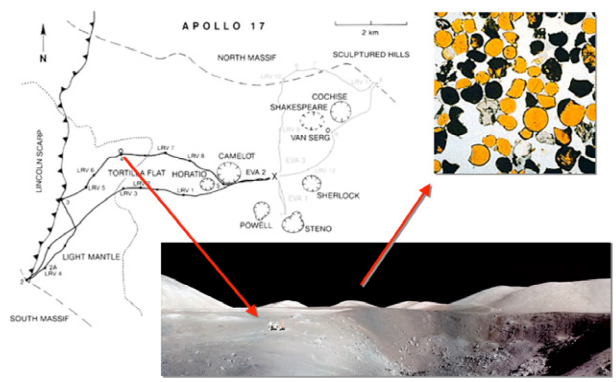

Fig. I: Orange glass discovered during Apollo 17 EVA #2, Station 4.

II. MOTIVATION

As an example of the utility of recon or follow-up, during Apollo 17 EVA #2, Jack Schmitt discovered orange glass at Shorty Crater. This was at Station 4 of the overall traverse, and remaining EVA time was limited. Had the presence of orange glass been known through surface reconnaissance, EVA #2 could have been re-planned to allow more time at Shorty Crater for the study, documentation, and sample collection of this highly important discovery. Or, alternatively, had Jack's EVA been followed up by a robotic sample return mission targeted at that location, the limited time available for human documentation and sample curation could have been extended by a long duration, systematic survey of the mineralogy and the return of larger quantities of sample material from several sites in the area.

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There are two different ways that robotic recon can inform EVA traverse planning. The first is to conduct recon far in advance of crew missions, to develop overall EVA traverses and tasks along the traverse. We refer to this mode as ”advance recon”. The second is to design a notional EVA traverse plan using remote sensing or other information, then conduct robotic recon along the planned route. Observations made along the route are used to modify tasks and adjust priorities. We refer to this as “lead scouting”. Advance recon offers more freedom in route planning but requires significantly more lead time and potentially greater coverage of putative EVA areas. Lead scouting offers a more targeted study of a designed EVA route, but can provide information to adjust the overall plan to maximize return [7]. Our experiments in robotic reconnaissance focus on the advance recon approach.

There are also many different ways robotic follow-up can be conducted. Follow-up activities could include taking additional measurements with in situ instruments, imaging and otherwise documenting a site, or sample collection, curation and return. Our experiments in robotic follow-up focus on the former.

Robotic scouting involves using a teleoperated surface rover to collect ground-level data prior to human field activity. Scouting is an essential part of field work and can be: (1) traverse-based (examining stations along a route); (2) site-based (examining stations within an area); or (3) survey-based (systematically collecting data along transects or grids) [12]. Robot-mounted instruments can measure the surface and subsurface at resolutions and from viewpoints not achievable from orbit.

We have studied the use of robotic scouting through a series of terrestrial field campaigns [9,10,11]. These test include operations concept inspired by remote rover operations, such as MER, as well as human spaceflight operations, including Apollo, Space Shuttle, and International Space Station [21,27]. Operations also include a science team working in a mode similar to the Science Operations Working Group (SOWG) for MER, and the Science Back Room from the Apollo era [25]. Our tests include an a priori remote sensing data analysis phase, an interactive real-time robotic surface exploration phase, and a simulated human crew EVA phase, to empirically evaluate the impact of robotic scouting on human EVAs.

Below we discuss the motivation for using robots as advance explorers, the empirical benefits of robotic scouting as an improvement over remote sensing data only, and discuss some open questions and recommendations for future work.

III. SYSTEM DESIGN

III. I Scientific Context

The scientific context for our work derives from four surface science scenarios of the type that were part of the Apollo missions to the Moon and were represented in the more recent lunar community-wide survey of objectives for returning to the Moon [23]. The tasks include lunar surface crew vehicle operations, lunar surface crew EVAs, in situ sample collection, geologic mapping, and geophysical survey.

Lunar surface vehicle mobility, crew EVAs, and sample collection and curation make up a critical piece of the Desert RATS operations. In order to study robotic reconnaissance in that context, our system was designed to leverage the available *a priori* environmental and operational data and pre-mission planning work, and to feed back into the vehicle traverse routes and crew EVAs planned for the Desert RATS field test. Recon data was used to replan routes as well as understand the context for *in situ* samples collected during science operations.

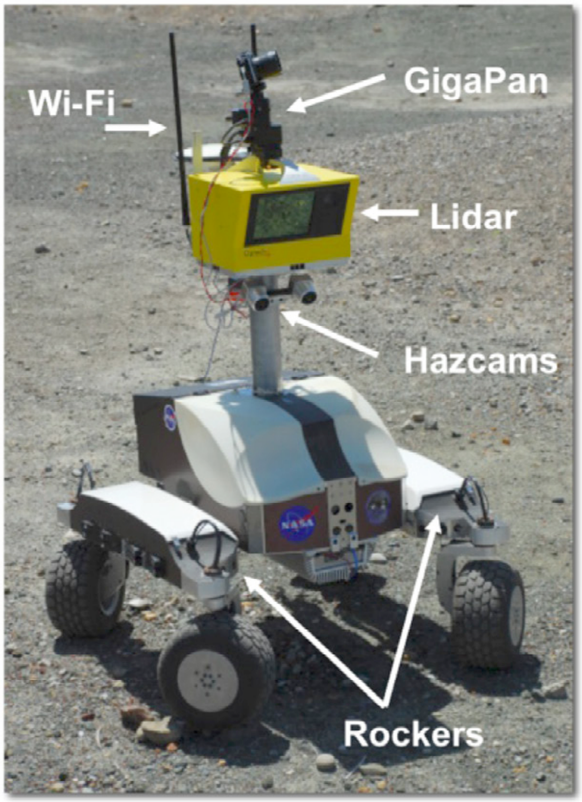
Geologic mapping and geophysical surveys serve as the scientific context for our robotic follow-up work at Haughton Crater.

III. II Rover Design

In this work, we used two third-generation “K10” planetary rovers (Figure II). Each K10 has four-wheel drive, all-wheel steering and a passive averaging suspension. The suspension design helps balance wheel/soil forces and reduces the transmission of motion induced by travel over uneven ground. K10 is capable of fully-autonomous operation on moderately rough natural terrain at human walking speeds (up to 90 cm/s).

K10 has mounting points on the front, back, and bottom as well as a 100 cm high mast. This allows attachment of antennas, sensors, and science instruments. K10’s standard sensors include a Novatel differential GPS system, a Honeywell digital compass, Point Grey Research IEEE 1394 stereo cameras, an Xsens inertial measurement unit, a suntracker, and wheel encoders.

K10’s avionics design is based on commercial components. The robot is powered by twenty-four (24) hot-swappable Inspired Energy 14.4V, 6.6 AH Li-Ion smart battery packs. K10’s controller runs on a Linux-based laptop and communicates via 802.11g wireless, or a Tropos mesh wireless.[4]



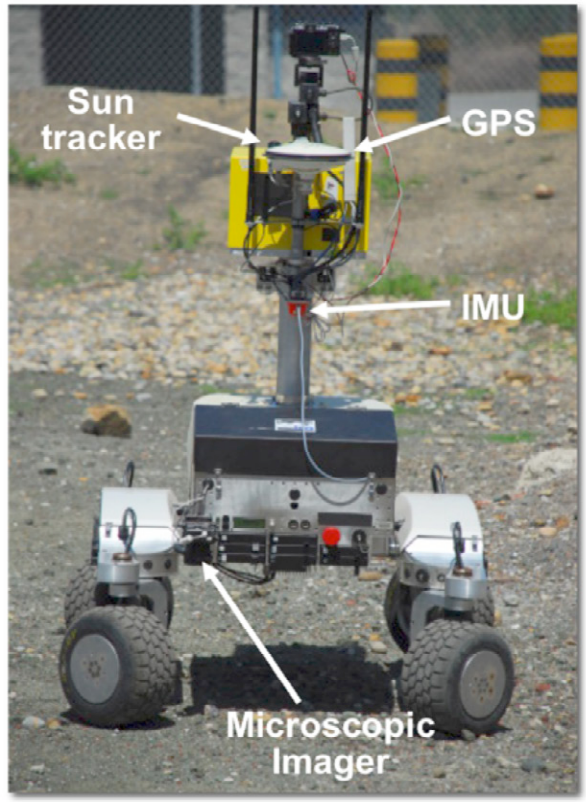


Fig. II: K10 Rover, as configured for 2009 Robotic Reconnaissance experiments at Black Point Lava Flow.

The K10 controller is based on our Service-Oriented Robotic Architecture (SORA) [8]. Major services include locomotion, localization, navigation, and instrument control. SORA uses high-performance middleware to connect services. Dependencies between services are resolved at service start. This approach allows us to group services into dynamic libraries that can be loaded and configured at run-time.

The K10 rovers are equipped with two science imagers: a custom panoramic imager ("PanCam") and a microscopic imager ("MI"). Both the PanCam and MI can provide contextual and targeted high-resolution color imaging of sunlit areas. These instruments are used both for science observations and situational awareness during operations.

The PanCam is a consumer-grade, 12 megapixel, digital camera on a pan-tilt unit. We operate the PanCam at 350 rad/pixel, which is comparable to the Mars Exploration Rover Pancam (280 rad/pixel). K10's PanCam, however, can be reconfigure for different resolutions by changing zoom. Images are mosaicked in software to create wide-field panoramic views.

The MI uses the same camera as the PanCam, but attached to K10 with a fixed, ground (nadir) pointing mount. At highest resolution, the MI provides 33 microns/pixel at the ground, which is comparable to the spatial resolution of the MER Microscopic Imager.

K10 carries Optech's Intelligent Laser Ranging and Imaging System (ILRIS-3D) on a central mast which places the instrument approximately 1 m above ground. The ILRIS-3D provides 3D scans over a 40x40 deg field-of-view from 3m to 1,500 m range, with an accuracy of 10 mm at 100 m. We use this instrument to make 3D measurements of terrain, examine surface texture, and assess terrain hazards in shadowed areas.

Other instruments carried by K10 but not pictured in Figure II include a ground penetrating radar (GPR) and X-ray fluorescence spectrometer (XRF).

GPR is a non-invasive technique for probing terrestrial and planetary sub-surfaces at different depths and resolutions using pulsed radio waves. GPR measures changes in signals induced by geoelectrical properties and structural heterogeneity. K10 carries the Mala X3M (Figure 5), which is a pulse repetition GPR. We employ a 800 MHz shielded antenna to perform subsurface mapping to 4 m depth.

The Niton XL3T is an XRF used for non-destructive chemical analysis of rocks, minerals, and sediments. We employ the XRF on K10 in order to perform real-time bulk analysis of geologic materials. In particular, XRF spectrometry is well-suited for identifying and quantifying (to first order) major elements in rock and soil, as well as for identifying trace elements (with abundances greater than 1 ppm).

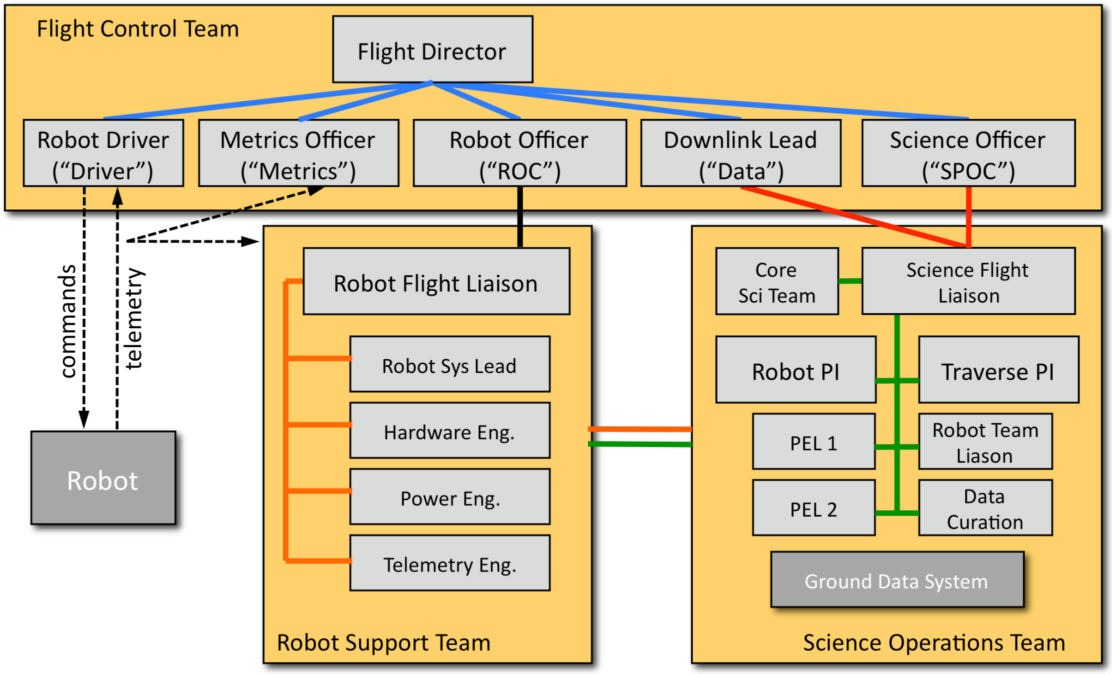


Fig. III: Ground control structure

III. III Ground Control Structure

We remotely operate the K10 rovers using a prototype ground control structure (Figure IV) that we have been developing since 2008[12]. This ground control structure is intended to support interactive planetary science robotics, such as remote operations on the Moon from Earth ground control. The structure's design draws inspiration from the ground control used for Apollo, the Space Shuttle, the International Space Station, MER, and the planetary rover field tests that we have conducted during the past several years[9-14].

Ground control operations are partitioned into three sub-teams: Flight Control, Science Operations and Robot Support. The Flight Control team is responsible for interactive, tactical decision-making and control. The Science Operations team is responsible for planning robot activities based on science objectives and for analyzing data acquired by the robot. The Robot Support team responds to robot performance and health issues, as well as provides technical support to the other teams.

The Flight Control Team conducts overall monitoring, commanding and real-time response of the robot and its major subsystems. The team has a hierarchical chain-of-command involving six positions:

Flight Director. "Flight" is the executive in charge of ground control. He coordinates and reviews information from the Flight Control Team and makes decisions to achieve mission objectives.

Robot Driver: "Driver" is responsible for robot mobility and real-time science ops (e.g., interactively panning cameras to look at specific targets or direction).

Metrics Officer: "Metrics" monitors robot performance to determine task progress and completion.

Robot Officer Coordinator: "ROC" monitors and controls all robot subsystems. He reviews and coordinates information from the Robot Support Team to handle contingencies.

Data Downlink: "Data" manages data communications with the robot, including the communications link and data transfers.

Science Protocol Officer Coordinator. "SPOC" represents the Science Operations Team. He provides explanation about robot plans, monitors science telemetry, and performs real-time science decision-making.

The Science Operations Team functions much like the MER Science Operations Working Group (SOWG)[21]. For interactive planetary science robotics, operations are potentially continuous and low-latency, so our planning cycle is designed to be rapid and iterative throughout the mission. This team is comprised of an overall Science PI supported by participating scientists and instrument experts.

One distinctive position in the Science Operations Team is that of Plan Lead. This person maintains communications with "SPOC" during execution of the current robot plan and coordinates development of the next plan to be executed. When execution and planning is complete, the Plan Lead rotates with SPOC in order to bring the new plan to the Flight Control team. In this manner, the Science Operations Team is able to be responsive and adaptable to contingencies and serendipitous opportunities.

The Robot Support Team provides real-time support to the other teams in different ways. For Flight Control, the team provides expertise on specific robot subsystems (hardware and software) when issues are beyond the ROC's knowledge or ability to analyze or debug a situation. For Science Operations, the team provides advice on robot performance (e.g., where the robot can, and cannot, operate) as well as payload operations (e.g., whether there are any concerns about using a particular instrument).

All of the ground control teams coordinate and communicate through voice loops and instant messaging, which are partitioned according to team. Communication between teams is generally initiated using point-to-point links. Once initiated, however, the conversation can be taken to the appropriate voice loop. For example, an instrument specialist from the Science Operations Team might speak on the Flight Control voice loop to explain unexpected instrument readings.

IV. ROBOTIC RECON EXPERIMENT

IV. I Robotic Recon Overview

On June 14-26, 2009, we conducted a test of robotic recon at Black Point Lava Flow, Arizona, USA. The K10 Robot was used to explore a planned traverse route designed for the Lunar Exploration Rover (LER). The goal of the test was to improve our understanding of how robotic scouting can help plan EVAs, and how robots might best complement human crews.

The experiment assessed the impact recon had on planning and executing simulated EVAs by two Desert RATS crews, with a comparison of the planning and execution under conditions relevant to lunar exploration with and without recon data.

The objective of the 2009 HRS Robotic Recon field experiment was to assess the effect of robotic recon on EVA traverse planning and crew performance. We designed an experiment to focus on: 1) examining the extent robotic recon can reduce uncertainty and improve science merit of traverse planning prior to human field work and 2) examining the area in depth in advance of EVA to improve crew efficiency and data quality.

This experiment took place in four phases (Fig. XII). In the Pre-Recon phase (through 1 June 2009) the traverse planning team planned two traverses, N1 and W1 (for North and West areas) and identified high priority areas where more detailed information was needed to better assess the science merit of a site, or to better assess the accessibility or trafficability of an area. These became the pre-recon traverses and the and the high priority recon objectives to answer science and

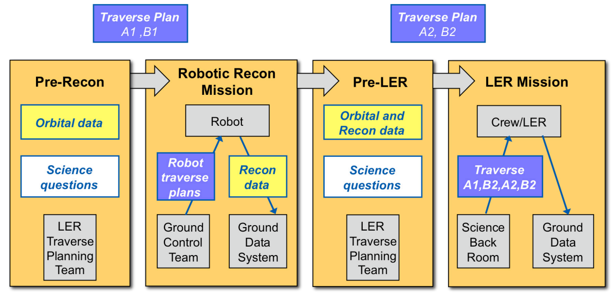


Fig. IV: The four phases of our robotic reconnaissance experiment.

operational questions.

In the Robotic Recon Mission phase (14-26 June 2009) the K10 ground control team conducted real time remote operations of K10, and collected imagery, video, instrument data, and operational experience from the two planned traverses. We also recorded video and voiceloops from the ground control team, and collected notes and statistics from operations for later analysis.

In the Pre-LER phase (27 June - 1 September 2009), after the robotic recon phase was complete, the notional LER traverses N1 and W1 were updated using information collected by K10 to generate traverse plans N2 and W2. Science priorities, operational issues, and details about the site that were not detectable from satellite imagery all influenced the plans. The changes in the plans were evaluated to quantify the impact of recon on mission planning before the plans were even executed.

During the LER Mission phase (1-18 September 2009) the LER crew carried out all four traverse plans with real time support from the ground control team. We recorded voiceloops, and collected notes and statistics from operations for later analysis.

As a control, a field geologist collected ground truth for, and evaluated, each pre- and post-recon science target and each recon target. This includes deleted targets from pre-recon traverse plans, and recon targets that were not added to post-recon plans.

IV. II Robotic Recon Objectives and Methodology

The recon experiment had two objectives: evaluate the effect of recon on the traverse plan, and evaluate the effect of recon on the traverse. Each objective had associated hypotheses, and each hypothesis had associated metrics and evaluation critera. These are summarized here. A more detailed explanation appears in [14].

Objective 1 was to evaluate the effect of robotic recon on the traverse planning process. We hypothesized that robotic recon would improve traverse planning by reducing uncertainties within a plan and enabling more concentrated effort in sites more certain to yield significant science.

Hypothesis 1A stated "robotic recon will improve the science merit of a traverse plan." This hypothesis was evaluated against the traverse science merit rating from the Pavilion Lake Research Project [Lim]. The science team estimated the science merit of each target of the two pre-recon traverse plans, and the two post-recon traverse plans. Differences in the pre- and post-recon traverse merit were associated with the impact that recon has on traverse merit. Additionally, ground truth collected by a field geologist was used to estimate an absolute merit rating based on first-hand experience rather than pre- or post-recon remote sensing and remote rover in situ measurements.

Hypothesis 1B stated that "robotic recon will significantly change a traverse plan in terms of time spent at science target and the number and nature of planned tasks." This hypothesis was evaluated against the time at each target, the number of tasks at each target, and a qualitative measure of the change to the plan (insignificant, small, medium, large, or complete change). Estimated times at each target were recorded on data sheets and completed before execution of traverse plans. During the LER mission, crew verbally communicated to the CAPCOM when they arrived at and departed from a target. Times were recorded using data sheets and the time spent at each target was calculated. Numbers of tasks will be counted and recorded on data sheets. This may be completed prior to the BPLF field test. Qualitative change to plan will be assessed by the science team and recorded on data sheets.

Hypothesis 1C stated "Robotic recon will reduce the operational risk of a traverse plan." This hypothesis was evaluated against a rating of operational risk. All operational teams (flight director, robot engineering, communications, etc.) estimated the operational risk of each target of two pre-recon traverse plans using a scale of 1 to 5. The addition of ground data from robotic recon was expected to reduce uncertainty and alter the operational risk ratings of targets. After traverse execution, the operational teams re-evaluated the risk ratings. A field geologist also collected ground truth on the presence of hazards in the field.

Hypothesis 1D stated "robotic recon will reduce the uncertainty contained within a traverse plan in terms of science merit and operational risk." While rating science merit and operational risk, the science team and operational teams will also indicate a degree of certainty (error bars) in their ratings using a scale of 1 to 5. This is distinct from the science merit or operational risk, it is more of a measure of the degree to which the team understands the science merit or operational risk in the face of uncertainty or missing information. Additional information gained through robotic recon was expected to decrease self-reported ratings of uncertainty.

Objective 2 of the recon experiment was to assess the impact of robotic recon on crew productivity. We hypothesized that robotic recon would impact the amount of time a crew spends on a station both operationally, for example in finding the right approach to a target with the LER, and scientifically, in terms of number, type, and duration of science tasks.

Hypothesis 2A stated "robotic recon will improve the productivity of a traverse." This was measured by a weighted sum of completed traverse objectives. The metric was based on the PLRP science merit and data quality metrics [20] but applied to individual traverse objectives rather than a traverse as a whole.

Hypothesis 2B stated "Robotic recon will improve the accuracy of traverse timelines." We hypothesized that traverse timelines estimated with recon information would be more accurate. We compared estimated timelines from the pre- and post-recon plans along with actuals from the traverses as executed.

Hypothesis 2C stated "Robotic recon will increase the number of get-ahead tasks performed." When the crew get ahead of schedule they may perform "get-ahead" tasks. Increased efficiency in carrying out the nominal plan should also impact the crew's ability to perform some get-ahead tasks.

Hypothesis 2D stated "Robotic recon will reduce time on-task." We hypothesized that better information about the task, and better situational awareness while conducting the task, should make tasks easier to complete in a shorter amount of time. Completion times were recorded during execution and compared.

IV. III Robotic Recon Results

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. In our results, the qualitative change between the pre-recon (W1) and post-recon (W2) traverses was significant. 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. 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 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).

We also encountered anecdotal evidence of the improvement in crew situational awareness. During the N2 traverse, the crew and back room were having trouble navigating and communicating due to networking problems, but when the crew visually spotted a terrain feature that had been prominent in a PanCam image from the recon data, they were quickly oriented and knew which way to drive. It is not clear whether that same visual recognition would have happened without the high resolution and ground based perspective of *in situ* recon data.

V. ROBOTIC FOLLOW-UP EXPERIMENT

V. I Robotic Follow-up Overview

On July 16 2010 through August 5 2010, we conducted a field test and mission simulation of a robotic follow-up system with a robot at Haughton Crater, on Devon Island, Nunavut, Canada, and a mission control center at NASA Ames. During the test, K10 Black was used to conduct high priority field observations identified by human crews during simulated EVA's conducted at the same field site in 2009. The goal of the test was to improve our understanding of how robotic follow-up can help improve the overall productivity of human and robotic partnerships, and how robots might best be used to complement human crews. Our test showed that robots can be useful by collecting lots of data that the human crew did not have time for, increasing the overall productivity and under-standing of the human-robotic team.

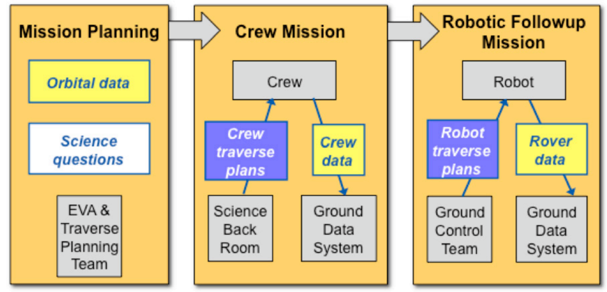


Fig. V: Crew mission results flow into robotic followup, allowing crew to identify high priority tasks.

V. III Robotic Follow-up Approach

This experiment consisted of three phases with two field missions. Phase 1 was an overall campaign definition and planning phase. Well in advance of a human mission, a science team will plan a traverse involving the use of a crew rover, such as the Lunar Electric Rover[10]. The science team will use any available a priori data of the traverse area, including orbital remote sensing. Phase 2 was the Crew Geotechnical Survey Mission at Haughton Crater that was operationally relevant to addressing important science questions on the Moon, in particular regarding regolith characteristics, impact compaction history, and near-subsurface structure. During the human mission, astronauts executed the traverse. During and after the mission, crews, ground operators, and scientists identified sites and tasks for robotic follow-up. They prioritized the follow-up work based on measurements EVA crews did not have time to make, sites they did not have time to visit, or questions that could not be answered with information from their EVA. Finally, Phase 3 incorporated the data acquired in Phase 2 to further plan and execute the Robotic Follow-up Mission at Haughton Crater. After the human mission, the science team used the mission data, the observations made, and the knowledge gained by the crew to develop a robotic mission. The robotic mission was executed in order to perform that follow-up work. This overall flow is shown in Figure V.

To ground our research in appropriate scientific context, we have chosen to conduct field work at Haughton Crater, on Devon Island, Canada. This field work focuses on two themes: (1) geologic mapping of the major lithologic units; and (2) geophysical survey of the near-subsurface.

In July 2009, we conducted the simulated lunar crew mission. A geologist (M. Helper) and a geophysicist (E. Heggy) planned traverses using a HMMWV as a simulated pressurized crew rover. Each traverse was performed by a two-man crew and included short EVA's on foot with unpressurized concept space suits.

In 2010, K10 Black conducted the robotic follow-up at the same field site, with the same geologists leading remote science operations at NASA Ames. K10 carried five instruments: a scanning 3D lidar, a color panoramic camera on a pan/tilt, a ground penetrating radar (GPR), an X-ray fluorescence spectrometer (XRF) and a high-resolution downward facing terrain imager.

The science team studied the results from the 2009 simulated mission and identified high priority science questions and specific targets for follow-up work. A ground control team remotely operated K10 to collect more detailed surface data. After robotic operations, the followup data was used to update the science team's knowledge and understanding of the two main science questions.

V. II Robotic Follow-up Objectives

The objective of the 2010 Robotic Follow-up field experiment was to investigate how robotic rovers may be used to perform "follow-up" work after human extra-vehicular activity (EVA) in order to improve lunar surface science. The primary objectives of the test were to (1) evaluate the impact that robotic followup after crew EVA has on overall science productivity, and (2) test our ground control, rover systems, ops and assessment protocols.

The overarching goal is to understand the nature of robotic follow-up as complementary and supplementary to human exploration.

The goals of this experiment are to identify *surface science scenarios* for human explorers to draw maximum benefit from robotic follow-up to vehicular traverses and EVAs, identify *science operations requirements* for conducting robotic follow-up on planetary surfaces after human exploration, and identify *mission operations protocols* for optimizing human field-work and robotic follow-up activities.

The objectives of this field experiment were to: (1) investigate the operational requirements for robotic follow-up at an analog field site of adequate relevance for lunar science priorities and science operations, (2) investigate the ground control and science operations structure requirements for supporting lunar analog robotic follow-up activities, and (3) investigate how follow-on robotic field-work can best extend, enhance, and complete tasks performed by humans.

V. Robotic Follow-up Results

From our 2010 robotic mission simulation, we learned that robotic follow-up can be useful for geological mapping. In particular, we found that K10 enabled us to further evaluate the structure of the inner wall of Haughton Crater, to map faults/fractures in rocks proximal to the crater rim, and to better understand the target sequence stratigraphy. For geophysical survey applications, we learned that robotic follow-up can provide precise metrics for quantifying the volumes, depths, concentration, and large-scale distributions of subsurface ice.

At Site A, one of our objectives was to use PanCam images to test, verify, and amend the geologic map developed by the crew mission. Of the PanCam images that were taken by K10 at Site A, seven provided useful views of the marker beds in the host carbonate stratigraphy. We analyzed two of these images and compared them to Quickbird satellite orthophotos to determine marker bed continuity and possible fault offset. The results are mixed. In a number of places the PanCam images appear to support initial interpretations, or are suffcient for re-interpretation of the map. In other locations, however, the data acquired by K10 is not informative enough to verify (or amend) the existing geologic map.

At Site B, the gently sloping northwest crater wall below the crater rim was observed during the crew mission to be composed of unconsolidated carbonate rubble: angular pebble- to cobbled-size clasts of dark to light brown dolostone similar to the target rock carbonate exposed at the crater rim. Low relief mounds, ledges and benches (observed with binoculars and visible in Quickbird imagery) comprise local topographic highs on this otherwise gentle and uniform slope. This rubble zone is a significant feature of the crater, a concentric ring of material that lies between the crater rim and a zone mapped as "dolomite slabs and blocks" which is, in turn, marginal to the white calcite breccias and melt sheet of the crater interior.

Robotic follow-up at Site B focused on addressing the origin of this carbonate rubble zone and of the local topographic highs within it. Data collected by K10 were used to evaluate four hypotheses, none of which were mutually exclusive. PanCam imagery of the northwest crater wall acquired by K10 supports a preliminary interpretation that the crater wall, though highly degraded, preserves evidence of fault-bounded terraces formed after impact as the crater rim collapsed inward. The images also show that the crater wall is also the site of at least one breccia block that is likely impact ejecta. The origin of this block remains unclear. It is either resting in a position that records ballistic emplacement or was emplaced by ice rafting from an indeterminate locale.

At Site A, we studied polygon features. Data from the MI and PanCam were used to determine surface roughness, grain sizes, and composition. Lidar was used to observe 3D surface features, particularly crack edges. GPR was used to map the depth to the ice layer. Based on the data collected, we determined that the average depth to the top of the ice layer is approximately 1 m.

At Site B, we used K10 to study the gullies along the northwest crater wall. MI data acquired at Locale 1 revealed thermally derived, poorly sorted angular rocks ranging from a few cm to 5 mm in size. PanCam images taken at Locale 2 showed signs of polygonal features in the soil. The random shape, size, and orientation of the polygons are consistent with a freeze-thaw process.

VI. DISCUSSION

In prior work[3,4,9-14] we identified significant differences between how robots have previously been used and what is needed for future human exploration. For ex-ample, past robot explorers (e.g., MER) were used as "primary science instruments", and not as tools to sup-port human explorers.

If we wish to use robotic follow-up as part of a coordinated human-robot exploration campaign, we need to understand the benefits, requirements, limitations and risks associated. Key issues associated with robotic follow-up are: (1) robotic rover capabilities; (2) Earth-based ground control; and (3) coordination between humans and robots.

Based on our field testing, we have confirmed several key differences between robotic exploration (e.g., as done by the Mars Exploration Rovers) and robotic follow-up. Most notably, whereas robot explorers serve as principal science tools, the primary function of robotic follow-up is to augment and complete human field work. This has significant implications for mission design and science operations.

There are, however, several important considerations to keep in mind. First, in order for robotic recon or follow-up to be effective, it is essential that there be good coordination between the work that humans and robots each perform in the field. Specifically, the efficiency, productivity, and benefit of robotic operations is highly coupled to the robot's mobility and instrument capabilities. Crew mission planning, therefore, needs to consider not only what humans will do (e.g., in EVA), but also what prior or subsequent robots will be able to do.

Second, accurate and consistent localization (particularly orientation) is needed to co-register data acquired by orbital remote sensing, human surface missions, and robotic follow-up. Although position estimates with limited accuracy (or even significant errors) can often be rectified through post-processing, interactive exploration missions will need real-time positioning that can be used by humans and robots alike.

Third, we have found that orbital remote sensing, human field work and robot follow-up are highly complementary. Each of these provides different types of data, viewpoints, and resolution. Individually none of these exploration methods is fully adequate or sufficient to fully explore planetary surfaces. However, by using all three methods in combination, we can improve the coverage, completeness, and quality of observations and measurements.

Overall, though development of human-robot science protocols and field procedures is still in its infancy, this experiment demonstrates the exceptional promise of robots to human exploration as a planetary exploration field technique. Our initial results indicate that robotic recon and follow-up are well suited to: (1) inform and refine human mission panning, (2) testing of hypotheses generated during time-limited human fieldwork and subsequent analysis; (3) refining and augmenting data gathered during crew traverses and EVAs; (4) rote or long-duration data collection (e.g. Lidar, GPR, etc.) tasks. Future work will seek to further confirm and quantify these benefits.

VII. CONCLUSIONS

Robotic recon and follow-up have many benefits over tightly coupled human-robotic cooperation. Specifically, this divide and conquer approach:

Makes good sense as Human Robot Interaction. Robotic recon makes good use of current state of the art robotics capabilities. Productive real-time human-machine interaction is still a significant challenge, but robotics technology is already up to the challenges of robotic recon. This maintains operational independence. It is unacceptable to design operations with crew waiting for a robot to complete tasks. Jack Schmitt has said, "I am still as 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, so that robotic activity supports EVA planning process, makes sense. Real time interaction doesn't." This is a different kind of "astronaut assistant" than the real time sidekick approach that has also been studied.

Can happen at a slower pace. Significant time is available for robotic recon. Even if the crew vehicle is used in an unmanned mode, it is likely to move more slowly than when the crew is onboard simply due to operational issues and the risk of teleoperation. But since there is significantly more time without crew on the lunar surface, recon does not need to happen quickly in order to be of tremendous value.

Does not need to determine everything. Robotic recon is not MER. MER is augmented significantly with MGS, MRO, and other orbital remote sensing, but the robots are the only assets employed in the ground-based study of Mars. The objective is to maximize the science of Mars through the robot. Robotic recon is not done in this mode. Recon is designed to support human crews. The objective is to use the robot to gather the best information for planning human EVA. There is therefore a significant difference in the science operations.

Does not need to make all the measurements, which means the instrument suite can be kept small. This minimizes mass, power, cost, and operations. A first robotic recon would look for the contacts before characterizing the rocks. The focus is on relationships, on making observations. This phase is less about sampling and more about understanding relationships.

Supplements and complements crew surface activity and remote sensing. EVA, while much higher in terms of intellectual resultion, is limited in duration due to the high risk and limited consumables required for life support. Remote sensing is fundamentally limited in resolution, viewpoint, and measurement types. Surface based telerobotic missions can provide ground truth for those things that are visible in remote sensing, and make up for many of the gaps that remain from orbital data or from human EVAs. It should be noted that this is task dependent. If the objective is to get the gross picture, then remote sensing may be sufficient. But if the objective is the details of the processes, then ground based data fills in a lot of detail.

Increases understanding of EVA and remote sensing data. Recon can help find things that are missed during a human surface mission, or difficult to discern in the remote sensing data. Some things are present but not obvious. One participant in our recent field test pointed out that “differences in the material on the rim of the crater were not detectable in the satellite image,” however another noted “It was visible in the remote sensing images after we saw it in the Pancam, we just didn't see it before.” Once something is found, that knowledge can be applied to other remote sensing data. In our Moses Lake field test, we applied observations made at one site to design EVA tasks at other sites that we expected to be similar based on remote sensing.

Improves Situational Awareness: The key to robotic recon is to give heightened situational awareness. Recon should focus on tools to provide data for human interpretation. During EVA’s, the crews know exactly what to look for and what to look at. Observations are much quicker to do, even when they are pressed for time. The question is “do you want to go into battle without any cavalry or recon or would you rather have it?” The most important thing is to have a lay of the land before you go out on EVA (this is the primary value). It's not so much replacing what the humans can do, but rather preparing for them.

Increases Productivity. Astronauts’ time is the most valuable thing; it is highly valuable to improve crew productivity. If you have a sense of what is there ahead of time, then you have more time to focus on things when you are there. In the context of human robot teaming, the important thing to optimize is not the efficiency of robots, but the efficiency of humans. For this reason, the impact of robotic reconnaissance should be measured by assessing the efficiency of crew EVA with and without information from robotic recon. Either advance recon or lead scouting will have this impact.

Improves science return and likelihood of success. According to Mark Helper, a field geologist will “often spend so much time stumbling around looking for the one key thing that puts it all together,” and can’t be sure ahead of time what particular observations or samples will be the key. Finding the Rosetta stone for the site under study requires that you “cover as much ground as possible. The more information you have before you start, the greater your chances of finding the thing that makes it all fall into place.” Robotic recon provides a lot more time to look for those key observations.

The robot also does not need to do all tasks. Sample collection, for example, is a much easier task for a human to do. But a recon robot will provide significant documentation support so that the crew can collect samples efficiently and the recon data will provide context for the samples collected.

Considering robotic deployments before and after human missions makes sense. A rover mission to the Moon would have to consider everything we learned through the Apollo missions even though those missions were never designed with robotic follow-up missions in mind. Future human missions to the Moon, Mars, or near earth objects should be designed with robotic precursors or robotic follow-up missions in mind.

MER science operations were designed to optimize science given that the robot is the only surface asset in use. While humans may one day set foot on Mars, there is no real near-term opportunity to consider their EVA activity as the next step in MER science operations. Apollo surface missions were also one-time visits to a site, requiring broad observations and documentation as well as detailed sampling simultaneously. Robotic recon and follow-up provide an opportunity for a sequence of visits to a site, with robotic high-grading, followed by intensive and more highly focused sampling and in-situ analysis by humans, and long term presence and detailed analysis and documentation by robots.

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