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Robotic Site Survey at Haughton Crater

Terrence Fong, Mark Allan, Xavier Bouyssounouse,
Maria G. Bualat, Matthew C. Deans, Laurence Edwards, Lorenzo Flückiger,
Leslie Keely, Susan Y. Lee, David Lees, Vinh To, and Hans Utz

Intelligent Systems Division
NASA Ames Research Center, Moffett Field, CA 94035

Abstract

In Summer 2007, we field-tested a robotic survey system at Haughton Crater (Devon Island, Canada). Two NASA Ames K10 planetary rovers performed systematic surveys of several simulated lunar sites, including a roughly 700m x 700m region called Drill Hill. The rovers carried a 3D scanning lidar for topographic mapping and ground penetrating radar to map subsurface structure. In this paper, we describe our robotic survey system, present the results of the field test, and summarize the lessons learned.

1. Motivation

When humans return to the Moon near the year 2020, it will be to establish a permanent presence. Detailed surveys will need to be carried out at a variety of locations for site planning (landing zones, infrastructure installations, etc.), for resource prospecting, and for lunar surface operations (including crew sorties). If surface operations require activity near (or in) a polar crater, surveys will have to be performed on rugged, often steeply sloped terrain and in permanently shadowed zones. Moreover, these mapping activities will require dense, systematic coverage of large areas with a variety of instruments.

Although data acquired from lunar orbiters (Kaguya, Lunar Reconnaissance Orbiter, etc.) will provide wide area coverage, resolution will typically be on the meter to kilometer scale. Topographic anomalies, rock size distributions, and regolith textures, however, vary laterally and vertically on sub-meter scales. These smaller-scale variations can only be documented by detailed surface surveys. Moreover, the need to ground-truth orbital data and to make contact measurements (e.g., bearing strength), also require that surface surveys be performed.

The difficulty with site survey is that hundreds (or thousands) of repetitive measurements may need to be made at precise locations or along specific transects. As a result, it would be *unproductive* for crew to manually perform such surveys through extra-vehicular activity (EVA) alone. For example, the total duration of lunar EVA during all of Apollo was 80 hours, which is less than half the time required for the survey operations during our Haughton Crater field test. For lunar site surveys, therefore, it is clear that some level of automation will be required.

To address this need, we are developing a system for performing systematic site surveys with multiple robots[5][6][7]. Unlike short-distance traverses and isolated sampling tasks, such as those carried out by the Mars Exploration Rovers, site survey requires area coverage with significant traverse in a bounded region. Consequently, the operations model previously used for planetary rovers (i.e., precisely scripted sequences for short command cycles)[9] is inappropriate for survey. An important goal of our work, therefore, is to develop operational concepts and procedures that are appropriate for robotic survey.

2. Haughton Crater site survey field test

From July 10 to August 3, 2007, we conducted a field test of our robotic survey system at Haughton Crater (Devon Island, High Arctic, Canada). Two NASA Ames K10 rovers surveyed lunar analog sites with instruments to map local topography and subsurface structure. Rover operations were designed to simulate a near-term lunar mission, including use of orbital data, interactive robot user interfaces, and remote operations procedures for intra-vehicular activity (IVA) and ground-control. The Haughton-Mars Project base camp[1] served as a proxy for a lunar outpost.

Haughton Crater is a 20 km diameter impact structure. It is a scientific and operational terrestrial analog for both the Moon and Mars. Haughton is similar in scale to Shackleton Crater, one of the primary candidate sites for a lunar outpost. The impact structure is an excellent lunar analog for several reasons: (1) extreme environment (polar desert, frozen subsurface, high UV flux), (2) relevant geologic features (mixed impact rubble rich in ground ice, ejecta blocks and rock similar to materials and terrains found on the Moon), and (3) isolated location with limited infrastructure (relevant for conducting high-fidelity simulations of lunar surface missions).

During the field test, we conducted surveys at several sites, which were selected to represent a variety of lunar terrains in terms of slope, composition, scale and remoteness. One survey focused on mapping “Drill Hill”: a remote 700x700 m region located approximately 5 km (a 30 min drive on an ATV) from the Haughton-Mars Project base camp.

3. Robotic survey system

Our robotic survey system uses planetary rovers equipped with survey instruments to perform systematic site surveys. With our system, rover activity is remotely coordinated from a nearby habitat (e.g., a lunar outpost), inside a surface vehicle (e.g., a pressurized crew rover), or from ground-control. A typical scenario involves multiple survey robots mapping a region while human operators assess the collected data and remotely intervene when necessary.

3.1. Survey hardware

During the field test, we used two third-generation K10 rovers, “Red” (Figure 1) and “Black” (Figure 2) equipped with survey instruments. The K10's have four-wheel drive and all-wheel steering with a passive rocker suspension. This design allows operation on moderately rough natural terrain at moderate walking speeds (up to 90 cm/s). Each K10 is equipped with a variety of navigation sensors: carrier-phase differential GPS, electronic compass, sun tracker, wheel odometry, stereo cameras, and a 2D laser scanner. Survey instruments are mounted on a mast or the central body.

Figure 1. K10 “Red” with a mast-mounted Optech ILRIS-3D lidar at Haughton Crater.

The K10's operate with a Linux-based controller (running on a dual-core Pentium laptop), 802.11g wireless communications, and a service oriented robotic architecture[4], which makes use of the NASA Coupled Layer Architecture for Robotic Autonomy (CLARAty)[13]. At Haughton, the K10's carried two, non-contact survey instruments: the Optech ILRIS-3D scanning lidar (used for topographic mapping) and the CRUX ground-penetrating radar (used for subsurface structure mapping).

Optech's Intelligent Laser Ranging and Imaging System (ILRIS-3D) is a scanning lidar designed for terrestrial survey. The ILRIS-3D measures 32 x 32 x 22 cm and provides 3D scans (40 deg x 40 deg field-of-view, 3 m to 1,500 m range). For the Haughton test, we mounted an ILRIS-3D on K10 “Red” (Figure 1) and captured full (360 deg) panoramas by turning the rover in place.

Figure 2. K10 “Black” with the CRUX GPR (mounted under chassis) at Haughton Crater.

Originally developed for the lunar “Construction and Resource Utilization Explorer” (CRUX) project by NASA JPL, the CRUX ground-penetrating radar (GPR) is a short-pulse system that operates at 800-MHz (center frequency)[8]. For the Haughton test, we mounted the CRUX GPR on K10 “Black” (Figure 2) and configured it for shallow penetration (2.5 m depth) and high resolution (10 cm), as would be used for lunar resource (e.g., polar volatile) prospecting.

3.2. Survey software

In our robotic survey system, software components run off-board (at the operator station) and onboard each robot. The system involves three phases: planning, execution, and analysis. In the planning phase, we use satellite images and instrument-specific coverage planners to compute survey points and intermediate waypoints. In the execution phase, a task executive dispatches tasks to the robots and monitors execution. In the analysis phase, we process survey data and telemetry logs into derived data products.

An important aspect of our system design is that robots operate independently and simultaneously. During survey execution, the K10's navigate autonomously and drive continuously in order to efficiently traverse the survey path. If a contingency, or exception, arises during operation, the K10's signal the operator for assistance. This operational model is significantly different from what has previously be used for planetary rovers, e.g., daily uplink/downlink command-cycles for short-distance traverses.

3.2.1. Survey planning. In the planning phase, we manually designate survey zones and areas to avoid (i.e., regions deemed unsafe or uninteresting) using high-resolution satellite images viewed in Google Earth. If stereo satellite imagery is available, we also construct a 3D terrain model and perform automated traversability analysis to distinguish safe terrain (regions the robots can safely traverse) from hazardous terrain (regions the robots must avoid). We then employed semi-automatic coverage planners to compute survey paths, taking into consideration instrument-specific constraints (e.g., parallel line transects for GPR survey).

To prepare for the field test, we employed 60 cm/pixel panchromatic imagery of Haughton Crater taken by the QuickBird satellite. This resolution is similar to the imagery of the Moon that is expected to be returned by the Lunar Reconnaissance Orbiter. We registered the QuickBird images to hand-collected tie points to achieve sub-meter registration to UTM.

Coverage planning involves dividing a site into a set of survey points and determining the order to visit each point. Common methods for spatial coverage planning include: line transects, zigzag coverage, and equal area subdivision. In practice, however, we cannot rely purely on spatial planning, but must also consider instrument-specific constraints (sampling rate, traverse speed, etc).

For topographic mapping, we used the ILRIS-3D lidar to acquire 360 deg panoramas. Lidar survey points, therefore, should ideally be uniformly distributed throughout the survey region, taking into consideration the average working range of the instrument. Wide-area coverage of terrain is achieved by merging panoramas taken at multiple locations into a coherent model. Although we did experiment with automated coverage planners, in practice we found that manually generated plans worked extremely well for most sites.

For subsurface structure mapping, we used the CRUX GPR to acquire parallel-line transects, which were spaced with no sensor overlap. To generate North-South and East-West transects, we performed a cell-based Boustrophedon decomposition[2] of the designated survey zone. To satisfy sampling rate constraints, we additionally specified that transects be driven at a maximum speed of 0.4 m/s.

3.2.2. Survey execution. In the execution phase, we use a task executive to assign survey tasks, monitor execution of those tasks, and resolve conflicts that may arise. Throughout this process, no off-board communication is required. This enables survey operations to be robust in the presence of intermittent data network failures, operator inattention, etc.

With our current system, each robot has an onboard task executive, which is implemented using the PLan EXecution Interchange Language (PLEXIL)[12]. During survey, the executive dispatches tasks to the robot controller. These tasks fall into two primary categories: (1) navigation (drive to a survey point and to intermediate waypoints) and (2) data collection, which is survey instrument specific (e.g., acquire a sequence of lidar scans to build a panorama).

3.2.3. Analysis. In the analysis phase, we currently generate two data products: (1) digital elevation models, and (2) summarization of robotic survey performance. During the field test, we generated DEM's by merging multiple lidar panoramas with the NASA Ames Terrain Pipeline. We developed the Terrain Pipeline to produce 3D terrain models from a variety of range data (stereo images, lidar scans, etc) and sources (satellites, rover cameras, etc).

A key feature of the Terrain Pipeline is its ability to align and merge multiple DEM's. Given a set of DEM's, the Terrain Pipeline first searches for overlapping regions by identifying intersections among bounding boxes. Next, the Terrain Pipeline iteratively performs pairwise DEM alignment. Finally, a global alignment method is applied, in order to propagate pose corrections throughout the entire DEM set.

Our robotic survey system is designed to support intermittent supervision of robot activity. A significant consequence of this mode of control is that "fan-out" [10] is increased: a single operator is able to supervise multiple robots (i.e., effectively increasing the amount of work he is able to perform). This is highly beneficial for lunar missions because crew sizes will be small and crew time will be at a premium.

For supervisory control to be effective, however, it is extremely important that humans be able to rapidly assess what robots are doing and to acquire (or reacquire) situational awareness, particularly when problems occur. To facilitate this process, we have begun developing a software architecture (Figure 3) to automatically summarize robotic survey performance (during and after survey), as well as to alert users to important system events when they occur [11]. During the field test, we used this architecture to: (1) monitor data from both K10's, (2) compute survey performance measures, (3) build Web-based summaries of these performance measures, and (4) notify appropriate personnel when summaries were ready for viewing.

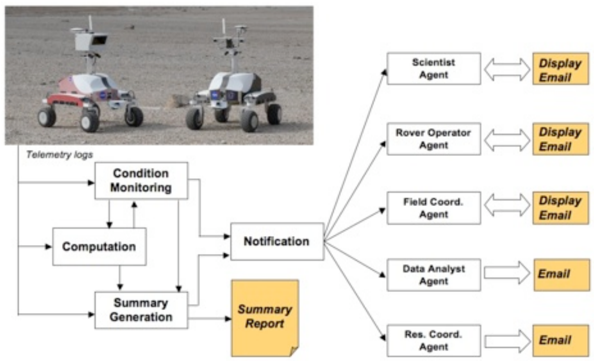

Figure 3. Summarization and event notification architecture

3.3. Remote operations

During the field test, we used several graphical user interfaces for robot control and low-level monitoring, the NASA Ames Viz 3D visualization system [3] to show robot state (position, health, etc.) and survey data, and Google Earth to display survey plans and monitor survey progress (with real-time updates) in wide-area geospatial context.

An important objective of the field test was to test two types of remote operations (Figure 4): (1) "lunar surface" mode using zero time-delay, high-bandwidth (54 Mb/sec), local wireless data communications and (2) "ground control" mode using satellite networking with variable time-delay and lower communications bandwidth (1 Mb/sec).

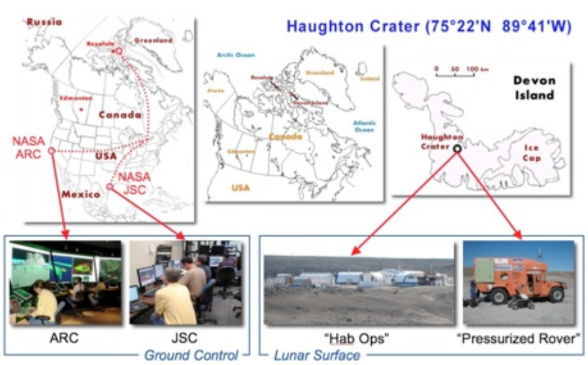

Figure 4. Remote operations: left, "ground control" mode; right, "lunar surface" mode.

3.3.1. Lunar surface control

Figure 5. HMMWV used to simulate a "pressurized rover" for Drill Hill survey.

We examined two modes of lunar surface operations: "Hab Ops" and "Pressurized Rover". Hab Ops simulated shirtsleeved IVA from a lunar habitat, with the Haughton-Mars Project base camp serving as a proxy. To simulate sortie operations in a pressurized rover, we stationed a HMMWV on Drill Hill (Figure 5) and used laptops as control stations, operating independently on-site for four days.

3.3.2. Ground control

To test ground control operations, we set up a satellite and ground data link between Haughton Crater and two NASA Centers. We simulated lunar ground operations at NASA Johnson (16-20 July 2007) and at NASA Ames (23-25 July). A three-person team monitored K10 Red and K10 Black survey performance via the remote link (Figure 6). Ground control operators also remotely drove the two rovers and processed lidar data to build 3D terrain models.

Figure 6. Ground control at NASA Ames.

4. Results

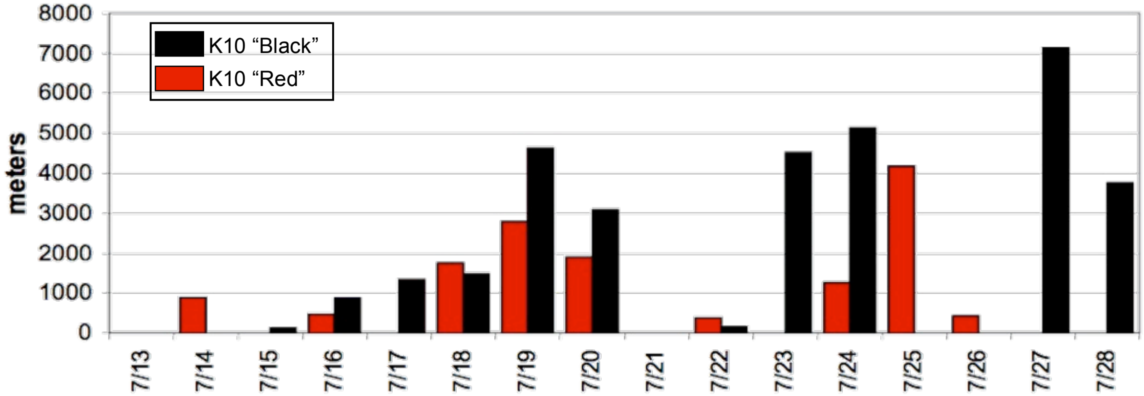

Figure 7. K10 traverse distances (by day).

4.1. Robotic survey performance

During the three-week field test, we performed more than 200 hours of robotic survey operations. Ten percent of these operations were conducted while the K10's operated outside of communication range, i.e., fully independently. The two K10's drove a combined total distance of 45 km (almost entirely autonomously) and returned more than 25 GB of survey data.

Figure 7 summarizes the distances traversed by each of the K10 rovers. K10 Red operated for 9 days, driving a total of 14 km on a wide variety of terrain while collecting 25 lidar panoramas. Figure 8 shows survey of a slope with 10-75 cm rocks. Figure 9 shows K10 Red obtaining lidar readings to several hundred meters. Figure 10 shows a Viz display with real-time telemetry and lidar-derived 3D terrain.

Figure 9. K10 Red operating on smooth, unobstructed terrain.

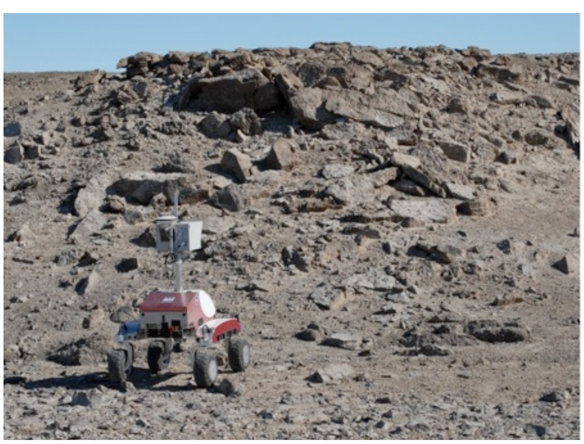

Figure 8. K10 Red scanning a steep and rocky slope during lidar survey.

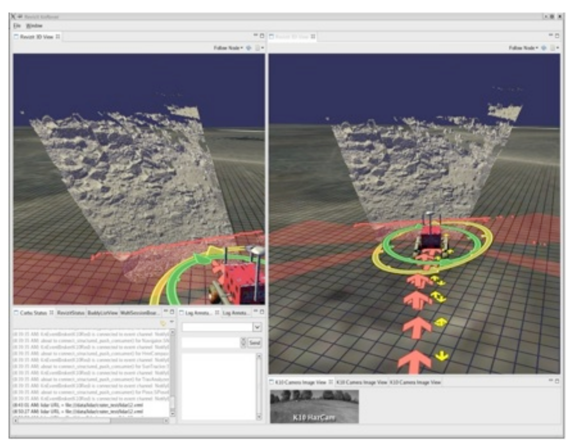

Figure 10. Real-time display of K10 Red telemetry and 3D terrain in Viz.

Figure 11. K10 Black operating in front of the Haughton-Mars Project base camp.

Figure 12. K10 Black surveying undulating terrain on Drill Hill.

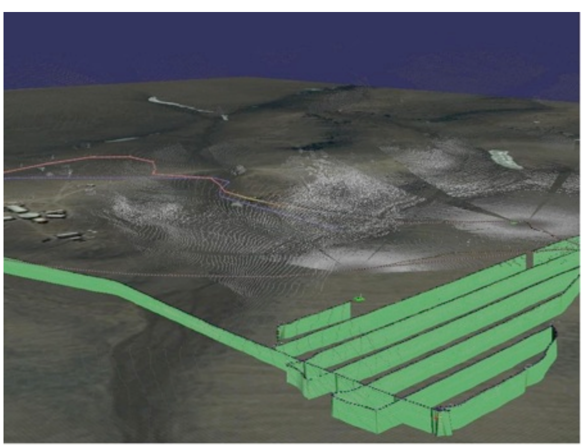

Figure 13. Data collected from GPR survey transects shown as vertical profiles in Viz.

Figure 14. Drill Hill survey plan and K10 Black path shown in Google Earth

K10 Black operated for 10 days, driving a total of 32.2 km while performing GPR survey. Figure 11 shows K10 Black driving on smooth, obstacle-free terrain near the Haughton-Mars Project base camp. Figure 12 shows K10 Black surveying on Drill Hill. Figure 13 shows a Viz display with a "ribbon" of collected GPR data (a vertical profile), which was continuously updated as K10 Black operated.

Figure 14 shows the results of the Drill Hill survey in Google Earth. The GPR survey plan (North-South and East-West parallel transect lines) is shown in green and the path traversed by K10 Black is shown in black. This screenshot was taken after completing four days of survey on Drill Hill, which represents 32 total hours of robot operations.

It is important to note that systematic survey often requires significant distances to be covered. For example, a rover simply crossing Drill Hill, which measures approximately 700x700 m, would need to traverse less than a kilometer. The systematic transect survey conducted by K10 Black, however, required a total of 20.5 km to be driven. As a point of comparison, this is approximately the same distance collectively driven by the two MER robots during 3.5 years of operations.

4.2. Terrain models

Throughout the field test, we generated terrain models from ILRIS-3D lidar scans. Individual scans were processed and displayed with Viz during survey execution. Figure 15 shows the "Fortress" formation and a 3D terrain model, which is rendered from approximately the same viewpoint. We also built numerous wide-area DEM's off-line with the Terrain Pipeline. Figure 16 shows a DEM of a valley that K10 Red surveyed. The hill in the distance is located 130 m from the robot.

Figure 15. Top, the "Fortress" formation; bottom, DEM of the "Fortress".

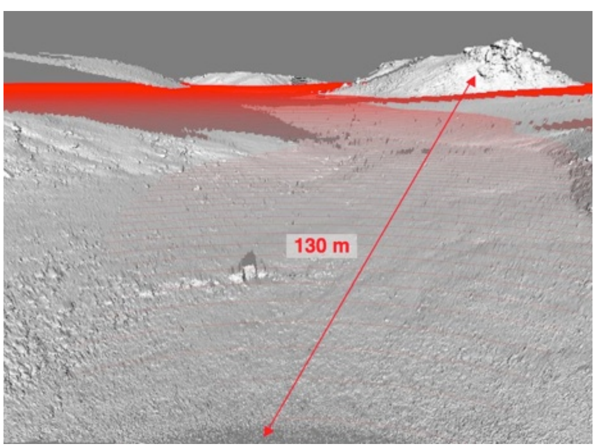

Figure 16. Valley DEM (1 m polar grid in red).

In addition to mapping terrain, we used the lidar and Terrain Pipeline to construct 3D models of man-made structures. Figure 17 shows a portion of the Haughton-Mars Project base camp, including the HMP greenhouse and solar panels (shown on right). This 3D model is a full triangular mesh with approximately two million points. The model was constructed from a panorama of 10 lidar scans (40 deg FOV per scan with 4 deg overlap between scans). The central "hole" in the model is the survey point about which K10 "Red" pivoted in order to acquire the panorama. The model is shown with textured overlay.

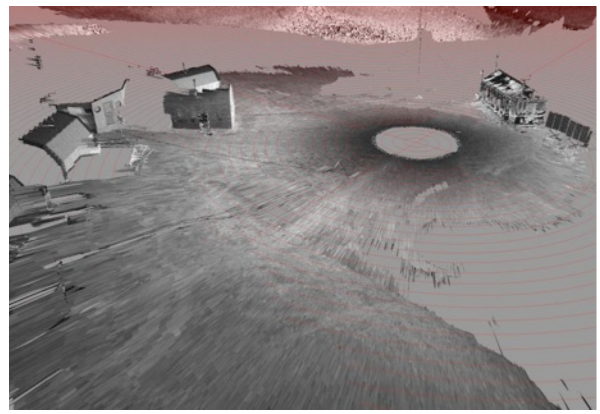

Figure 17. 3D model of Haughton-Mars Project base camp.

4.3. Auto summarization

During the field test, we automatically generated summaries for topographic and subsurface structure mapping. For each type of survey, we defined computations needed to build the summary, including: distance traveled by the rover; samples collected by the rover; run-time of instrument payload(s) on the rover; drive-time of the rover, and run-time of the rover. We designed each summary to provide information in the five areas shown in Table 1.

Table 1. Survey summary categories

Overview	Identifies the robot, the survey location, and time period.
Plan performance	Compares actual and planned distance traveled and samples taken.
Instrument performance	Summarizes the number of samples, the instrument run-time, and identifies problems (e.g., bad scans) where possible.
Robot performance	Summarizes robot daily and mission performance in terms of distance traveled, run-time, and drive-time.
Event log	Details specific events (nominal and off-nominal) that occurred.

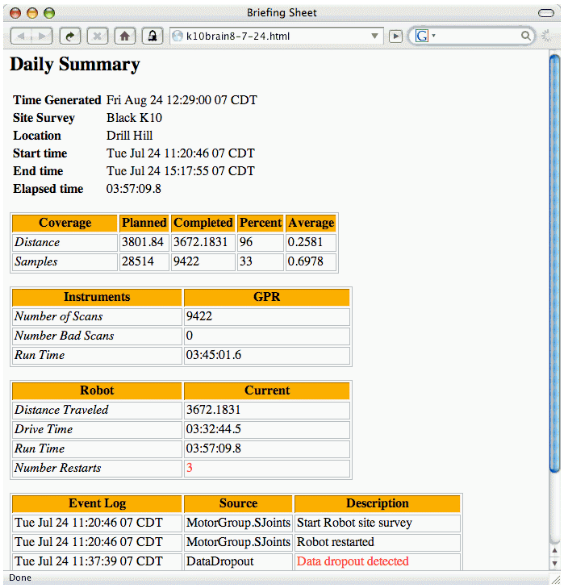

Figure 18. Example of an automatically generated daily summary.

Figure 18 shows a K10 Black summary displayed in a Web browser. During operations at NASA Johnson, we generated daily summaries in near real-time.

5. Conclusion

We learned several important lessons about robotic survey from this field test. First, instrument operational constraints have a huge impact on operations. Secondly, systematic coverage requires long distance driving. Although Drill Hill is only 700 m wide, dense GPR survey required 20 km of driving. Finally, intermittent robot control can be effective and enable an operator to perform other tasks or to supervise multiple robots.

We found that continuous navigation and locomotion significantly improves survey performance by enabling high-duty cycles. We also found that it is important to facilitate situational awareness, especially when intermittently monitoring robot operation. Combining multiple sources of information (robot state, survey plan, survey data, etc.) for geo-spatial display in Viz and Google Earth was particularly useful. Auto summarization helped facilitate awareness, as well as managing large amounts of archived data.

Overall, this field test demonstrated that it is clearly feasible to use robots to conduct systematic, comprehensive and dense site surveys. Consequently, we strongly believe that robotic site survey can significantly reduce the cost and risk of establishing permanent human presence on the Moon by relieving crew from having to manually perform a tedious, highly repetitive and long-duration task.

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