SCIENCE TEAM EXPERIENCE WITH AN AUTONOMOUS ROVER IN THE FIELD AND AUTOMATED SCIENCE ANALYSES.
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Introduction: The autonomous rover project of the Toolbox for Research and Exploration (TREX), a node of the NASA Solar System Exploration Virtual Institute, SSERVI, is investigating tools and techniques designed to improve operational efficiency and science yield of future rover missions. Field tests were conducted with the Carnegie Mellon rover, Zoë, in northern Arizona in November 2021 [1].

Approach: Before rover deployment, the science team analyzed AVIRIS imaging spectroscopy data at ~20 meters/pixel for the two chosen field sites, producing mineral maps using Tetracorder [2-4], and photointerpretation of visible color high spatial resolution (<1 meter) Google Earth images. The AVIRIS Tetracorder results were analyzed and initial hypothesis maps derived and delivered to the rover team for integration with the rover software.

A central server was set up to enable the rover and rover support field instruments to upload all operation and science data to the server so that the remote science team could monitor incoming data. The instruments on the rover included the following. 1) An RGB color camera, and 2) a reflectance spectrometer covering 0.35-2.5 μm, both mounted on a pan/tilt mechanism. 3) A Gamma Ray Spectrometer (GRS) which measured the radioelements K, Th, and U at regular intervals along the rover traverse [5]. Instruments not on the rover, but hand operated to simulate integration included: 1) a 0.18-0.96 μm UV-Visible spectrometer. 2) A 0.35-2.5 μm spectrometer with a configuration for contact measurements to provide reflectance data without gaps due to atmospheric absorption if the sun were used as the light source. 3) A contact FTIR instrument covering the 2.5 to 15.4 μm in reflectance. 4) A "microscopic" RGB color imaging camera provided close-up images of the locations where contact spectra were obtained. The "microscopic imager" was a cell phone camera. 5) An X-ray diffraction (XRD) field unit was used to determine sample mineralogy at selected locations.

The UV to mid-IR spectrometers, including data from the rover reflectance spectrometer, were calibrated on site before uploading to the science server. The rover computer ran Tetracorder to analyze the onboard reflectance spectrometer data to be used in autonomous rover decisions.

Science Analysis Automation: Data from the rover and rover team that were uploaded to the central server were pre-calibrated and available for immediate analysis by the science team. Thus, no calibration pipeline was needed once the data came to the science team. Field and science team notes and decision-making with choosing data points were recorded by the team documentarians. The Tetracorder system, has an expert system with spectral features defined for hundreds of minerals and other materials that cover the spectral range from 0.4 to 4 μm . Thus, this spectral region could be automatically analyzed. Automated analyses were performed real time as field data arrived on the central server and results were available to the science team with only a few second delay.

Tetracorder spectral analyses were automated for 3 spectrometers: 1) the rover 0.35-2.5 μm spectrometer, 2) the 0.35-2.5 μm contact spectrometer, and 3) the 0.25-4 μm portion of the contact FTIR spectrometer. Traditional "hand" spectral analyses were done for spectral regions not covered by the Tetracorder expert system, including UV and mid-IR interpretations. The XRD data were also analyzed after the field campaign. Elemental analyses were carried out on board the GRS data acquisition computer and were immediately available to the science team for the first site. Low-K GRS data acquired at the second site required revision of the data reduction software, such that the elemental data were not available until after conclusion of the field work. The traditional "hand" analyses took hours/days/weeks to complete, as schedules permitted.

Scenarios: We conducted 3 scenarios at 2 different field sites.

Scenario 1) The rover operated in a standard rover exploration paradigm where the science team chose waypoints. The rover was commanded to go to each waypoint, but chose autonomously the route to get there, and the rover obtained 0.35 to 2.5 μm spectra while driving to each waypoint. At each waypoint, the science team optionally requested imaging targets/activities (e.g., panoramas, specific imaging angles and directions). Based on analysis of rover camera images, the science team identified local targets to obtain contact spectra, XRD measurements and microscopic images.

Scenario 2) The rover was set up for autonomous rover exploration, where it was commanded to go from a specific initial to a final destination waypoint. The rover chose the route and intermediate waypoints based on the initial hypothesis map supplied by the science team before field operations but it was revised automatically thereafter as new observations were made (thus the exploration plan changed on the fly and was not fixed by the initial hypotheses). At each waypoint the science team could request imaging along with contact spectra, XRD measurements and microscopic images from locations selected in rover images.

Scenario 3) The rover was commanded to drive autonomously to specific waypoints along with a deployed astronaut. The astronaut could explore independently between waypoints, choosing any path (particularly to cover terrain or reach outcrops not accessible to the rover), and performing additional imaging and analysis activities and collecting samples. The rover and astronaut would meet up at each waypoint before proceeding to the next. The astronaut could choose alternate waypoints on the fly and request rover imaging activities, and specific XRD, contact spectra, microscopic images, and GRS spectral accumulations.

Experience: Field Site 1 was a training ground that helped the science team and rover field operations team to gain experience with the 3 scenarios. Field Site 2 was more challenging from operational (greater topography) and scientific perspectives and provided a more robust test of the autonomous science system.

The central server had 3 Tetracorder processes set up that analyzed spectra (from the rover and 2 contact instruments as described above) that gave the science team instant analysis of composition after the data arrived on the server. The data receipt on the central server was not real time. The rover periodically sent data to the server to simulate downlinks to Earth from a rover on a remote asteroid/planet.

In Scenario 1, between downlink periods, with the science team waiting for data, and the rover waiting for the science team to give instructions on what to do next, exploration was slow. In scenarios 2 and 3, with the remote science team not commanding all rover activities at each waypoint, exploration was faster. However, the rover still had to wait at each waypoint to check if the science team and/or astronaut wanted additional data. Delays were caused by the human science team assessing the received data. It was clear that additional automation would speed that process.

Because the UV and mid-IR analyses were performed by hand, results from these instruments did not feed into the rover decisions. XRD and gamma-ray data were analyzed after the field campaign was complete. Thus, the science team made decisions during the rover mission based on imaging and Tetracorder analyses in the 0.4-4 μm range.

In Scenario 3, the astronaut provided additional eyes on the ground, human experience and interpretation, enabling additional insights that the science team might miss based on limited data. The astronaut was hampered by not having direct access to the rover analyses and contact spectra results and by having limited to no real time communication with the science team (due to limited coms in the remote field locations). The astronaut was able to hold a rock up to the rover spectrometer and the rover could take a spectrum of the rock, but the rover had no readout of the Tetracorder result available in real time for the astronaut. Tetracorder has the ability to verbally tell the Tetracorder answers, and in our next field campaign we hope to have a speaker on the rover so the rover can talk to the astronaut. Or the rover needs a monitor to efficiently show results.

Results: The automation achieved in these first field tests were successful. The automated science results from spectroscopy were a clear help in understanding mineral composition at each location in rapid time. Based on comparison of the spectra that were hand analyzed, that took hours to days, versus the Tetracorder results that were obtained in seconds, the scientific understanding of each waypoint was sped up by orders of magnitude. With automation, more area can be explored in a shorter time, providing greater science return for a given cost.

The autonomous rover choose waypoints that were different than what the science team chose using the same beginning point and end point. But while different, they were equally valid, and both strategies produced interesting results.

Future: Further automation of the spectral range (the Tetracorder expert system) is planned. Integration of the gamma-ray results into real-time analysis, as well as XRD and greater spectral range will provide a better picture of the composition and geologic environment. Refinement of the data that is incorporated into the geologic origins and hypothesis map would also improve results of determining the geologic origin of the target materials.

If a future rover had an imaging spectrometer, imaging and spectroscopy would be better integrated. Tetracorder could analyze the imaging spectrometer data to more quickly find compositions of interest than can be done with the current point spectrometer on the Zoë rover. The rover could then decide autonomously to drive to interesting compositions found in the imaging spectroscopy results.

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