On Board Pattern Recognition for *In Situ* Science: Detecting and Prioritizing Rover Science Opportunities

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Continuation Proposal

Proposal Summary

Future planetary surface exploration missions with mobile robotic platforms will have the capability to collect more sensor data than can be transmitted to earth. To maximize the return on these missions, it will be critical that the platforms have the capability to analyze information on-board and select the data that is the most likely to yield valuable scientific discoveries. As the platforms become more autonomous in their navigation, it would be desirable to be able to take advantage of opportunities that are encountered in real time. The task described in this proposal is aimed at increasing the science return on such missions by developing algorithms for on-board detection and prioritization of science information collected by a rover. The approach proposed is to analyze the data that the rover can readily acquire and to use such analyses to aid in deciding what information to send back to Earth, where to take samples using the more time-consuming instrumentation, and which surface regions to explore further. Algorithms will both be developed internally and collected from external sources and will be evaluated in a testing framework that has been developed in the Computational Field Geology working group at JPL. The goal of this task is to produce a unified set of algorithms that can run on-board the FIDO (Field Integrated and Design Operations) field test rover which is closely related in architecture and instrumentation to the Mars Sample Return mission rovers (Athena) to be launched in 2003 and 2005. Funding is requested at a level of $175K/yr for the next two years.

Basic Ideas and Principles to be Investigated

The objective of this task is to develop and validate novel algorithms for detecting and prioritizing significant science opportunities onboard Mars rovers in general, and for the Athena class of science payload in particular. Mobile platforms are equipped with a variety of sensors, each of which has different resource requirements for taking sample measurements. The modalities on the Athena payload consist of imaging sensors and spectrometers. Panoramic camera (PANCAM) images, IR spectrometer readings and navigational camera images can all be sampled relatively quickly and frequently. In contrast the microscopic imager, Raman spectrometer, Mössbauer spectrometer and mini-corer require extended sampling periods. Thus, it is reasonable that a rover would use image information in conjunction with the IR spectrometer information to determine the location or rock that has the highest expected science return if sampled by the more expensive instruments. Since there is very little cost for taking these measurements, many more can be taken than can be commanded from the ground or than can be transmitted back to the ground. On-board analysis to determine the most scientifically rich data to return is necessary to maximize mission value. In addition, on-board analysis of the sensor data during a traverse enables the possibility of opportunistic science.

The project proposed here is to develop and evaluate the effectiveness of pattern recognition algorithms that analyze visual images and IR spectral data. In the past, instrument sample data were transmitted directly to the surface with no on-board analysis other than the use of stereo images for obstacle detection/range map calculation for navigation. We propose to analyze the sampled visual images using texture analysis, color information, and by combining stereo range map with texture. In particular, we will quantify our present performance and demonstrate a quantitative improvement by developing novel algorithms which (a) account for shadows, (b) cluster textures across views using correspondence and range data to include only pixels within fixed range bins, and (c) cluster texture/reflectance functions across views. *We also plan to coordinate with other researchers to incorporate related* *applications such as the 3-D modeling of Peter Cheeseman at Ames as well as texture and spectra analysis algorithms under development by Ted Roush and his colleagues at Ames.*

In the simplest mode of use, validated science feature detectors will be used to prioritize image data taken along traverses for transmission to Earth. Two important functions for pattern recognition in such a situation are to infer surface mineralogy classes (a) from remote point reflectance spectra (e.g. with specialized mineral detectors for an infrared point spectrometer) and (b) from geological texture (visual texture/color clustering from images). Building on an existing infrastructure for validating algorithms against ground truth elicited from geologists, we propose to focus on fundamentally improving the cost/benefit tradeoff for such algorithms by addressing the essential algorithmic questions of viewpoint- and illumination-invariance in spectral and geological texture processing. Several algorithmic approaches will be developed and tested. This work will be done strictly within the context of verifiable in situ *mineralogy detection, using the Computational Field Geology working group at JPL as the focal point for interactions between geologists (Anderson, Gilmore, and visitors from the Athena science team) and computer scientists and engineers. Scientific benefit will be measured by mineral class detection accuracy and also by the operational utility of the science prioritizations in well-defined scenarios, as communicated to FIDO rover system's software in which the science processing will be tested.*

Status and Accomplishments

In the first year of this task a software framework for testing the algorithms has been developed and populated with a number of image and spectrum data sets including some ground truth labellings [1,2], and with several new algorithms [3,4]. The framework enables comparisons among competing algorithms and allows for quantifiable assessment of algorithm performance. Algorithms that the Computational Field Geology working group develops and algorithms developed by researchers external to the working group are easily incorporated into the framework for direct comparison. The framework involves testing algorithms using data sets that have been collected and comparing the results to ground truth information provided by geologists. Currently included in the testbed are several algorithms for texture segmentation, segmentation using combined texture and color information, stereo range map estimation and spectral analysis for a specific class of mineral. Figure 1 shows the sequence of analysis of spectral data taken in the Mojave Desert near the FIDO field test site. A neural net is used to identify carbonate versus noncarbonate rocks.

In addition to the algorithms currently in the testing framework, we have obtained several other programs including a texture analysis program from Techniscan which was developed through a Small Business Innovative Reseach Award (SBIR). The test data set currently includes images from several different environments including FIDO Mojave desert images, images taken by FIDO in the Mars yard, images taken using a digital camera in the Mars yard (55 images), images of geology around the San Gabriel valley, Brodatz type texture images (3 images), Pathfinder images, point spectra data sampled in the Mojave desert at the site of the FIDO field tests (30 samples) and FIDO stereo pair test images. Some of these image test sets include systematic variations in viewing angle and distance. A number of hand samples were characterized mineralogically. Preliminary results using the algorithms thus far developed and collected are individually promising (e.g. Figures 2, 3) but not yet systematic. The FIDO field test results largely show site terrain being segmented according to the size and darkness of the rocks present. Algorithms are to be tested using a rover control software such as Rover Control Workstation (RCW) or Web Interface for Telescience (WITS) which simulate remote operations.

Uniqueness of Proposed Ideas

To maximize the scientific return on future missions with mobile platforms exploring planetary surfaces, each platform will need to be able to detect and prioritize science opportunities as they are encountered. The proposed use of visual texture, 3-D texture, color and spectral information combined and correlated across multiple samples is an innovative and novel approach to the data prioritization. The task proposed here will involve the development of algorithms to identify useful scientific data and thus will be able to cooperate with the proposed Surface Systems task "Optimized Rover Operations for Autonomous Science" (E. Baumgartner, PI). The latter task has proposed to develop methods for on-board processing and optimized sequencing of rover operations by applying science data utility models.

Other researchers within NASA have recognized the necessity of increased on-board scientific analysis. Researchers at NASA Ames have also begun to look into autonomous science for Mars rovers [5,6]. The Athena suite of instruments includes both visual imaging devices as well as spectral measurement devices, thus the researchers at Ames are addressing the analysis of visual and spectra information. Their work complements the task currently being proposed. Specifically, their texture analysis emphasizes the detection of layers in an exposed vertical surface rather than analyzing individual rocks for 3-D surface texture with the intent to infer clues concerning content and history. It does not yet incorporate stereo-derived range information or cross-view analysis. However, we hope to collaborate with researchers at Ames and elsewhere to bring wide variety of algorithms and combinations thereof into our testing framework. One example will likely be an interaction with Peter Cheeseman on superresolution and three-dimensional modeling.

Texture analysis has the unique ability to classify rocks on the basis of grain size, which can provide significant information about rocks of similar composition and heterogeneity within a single rock sample. Grain size can be an important indicator of rock genesis and evolution and, in combination with other data, enhances the scientific return of a particular scene. Two examples of the utility of texture classification to geological interpretation are described below.

Metamorphism. Figure 2a shows two rounded boulders in an arroyo near JPL. Microscopic analysis of the minerals in both boulders would reveal them as containing quartz, feldspar, and biotite classifying them as granites. Textural analysis (Fig. 1b) shows the rocks to have different textures that correlate with a larger average grain size in the rightmost rock. Textural and geological analysis of these data now lead to the interpretation of this rock as a metamorphosed granite, or gneiss. On Mars, metamorphism by impact can lead to rocks that have been remelted, but maintain the mineralogy of the original host rock. This along with surface weathering was a significant problem in the analysis of the Pathfinder scene, where despite *in situ* chemical analysis and spectra of the rocks, the origin of the rocks, whether igneous, sedimentary, or impact melt, remains equivocal [7]. Without classification of the rocks, we cannot evaluate whether the Pathfinder rocks of andesitic composition are associated with subduction zones, water and plate tectonics as they are on Earth, or derived from the complicated melting history associated with an impact onto the Martian surface. If the former, new paradigms would need be developed to explain ancient motions of the Martian crust and the derivation of these rocks from the Martian mantle.

Rock heterogeneity. Marked changes in texture occur within individual rocks and can be linked to several factors. In igneous rocks, grain size is indicative of cooling rate, where larger crystals cool more slowly (Fig 3). Grain size dependence on cooling rate is also a feature of evaporite mineral deposits. Evaporites and precipitates are associated with water and offer a mechanism for preservation of water-borne materials making these deposits a prime target for the search of life on Mars (e.g., [8]). Larger crystals correspond to deeper water, which may be especially important in reconstructing a scene with rocks that are not in their original positions. Detection of such distinct and desirable features such as variations in texture will allow a rover to effectively triage a geologic scene and prioritize scientific targets.

Customer Relevance

The emphasis of the proposed task is on rovers outfitted with the Athena instrument package, however the work is applicable to any mobile platforms exploring planetary surfaces. Such platforms will need to perform in-situ science analysis in order to explore significant planetary surface areas. Thus the proposed task is highly relevant to the Space Sciences Enterprise (S3 – Solar System Exploration). The proposed task is also relevant to the Human Exploration and Development of Space (HEDS) Enterprise (H3 – Exploration using Robotic Partners). Robotic platforms will be used to explore regions before humans arrive at Mars. When humans do arrive, preliminary scouting will be desirable so astronauts, who can spend only limited amounts of time in the field, can select scientifically or economically significant sites for exploration and sampling.

The principle investigator, Dr. Eric Mjolsness, received his Ph.D. in computer science and physics from the California Institute of Technology in 1985. His research activities have led to the publication of more than 20 journal articles, 7 book chapters and 30 conference papers in computational field geology and neuro-computing. Co-investigators Robert Anderson and Martha Gilmore are planetary geologists while Rebecca Castano has a background in pattern analysis and machine learning, Roberto Manduchi in image analysis and Terry Huntsberger has experience with data (visual and spectral) analysis algorithms onboard FIDO.

References

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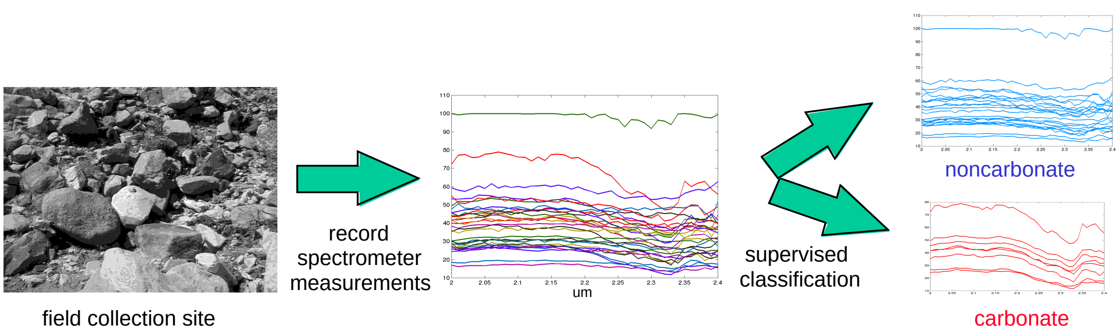

Estimation of presence of carbonate rock

Figure 1. *A supervised neural network is successfully able to distinguish the spectral field data that represent samples from carbonate rocks vs. those spectra that represent samples from noncarbonate rocks.*

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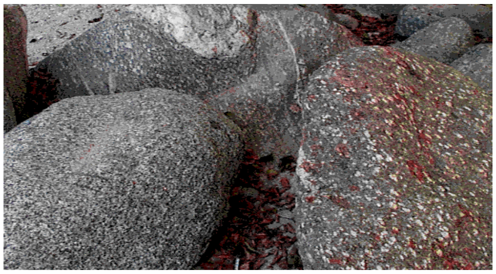

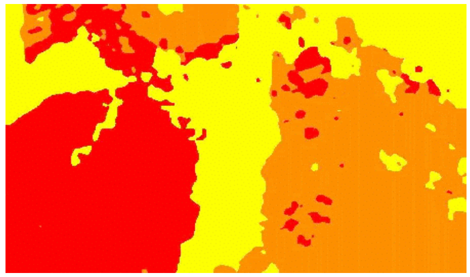

Figure 2. (a) Photograph and (b) texture clustering result of two boulders. Although of similar mineralogy, the boulders have different textures. The rock on the right has suffered a higher degree of metamorphism than its neighbor resulting in an increase in grain size.

Figure 3. (a) Photograph and (b) texture clustering result of a granodiorite rock face in the San Gabriel Mountains. The transition from large grain sizes (top) to smaller grain sizes (bottom) corresponds to faster cooling rates and closer proximity to the intrusion edge.

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X-MSMail-Priority: Normal
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To: Eric Mjolsness
From: Ray Arvidson
Sub: Relevance of Pattern Recognition Work
Date: 6/23/99

Eric-

I am the chief science coordinator of the FIDO field trials and rehearsals for the 2003 and 2003 rover missions with the Athena Payload. I am also the Deputy PI for the Athena Payload.

I support the concepts being developed in your proposal entitled:
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Specifically, I like the idea of using FIDO data to test algorithms for recognition of rock targets by texture and spectral characteristics. The hope is that these procedures can work on the 03 and 05 rovers and keep us from missing important features

Cordially,

Ray Arvidson
Washington University