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Science on the Fly: Enabling Science Autonomy during Robotic Traverse

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Abstract— **Robotic explorers must be capable of autonomous navigation into unknown terrain as well as autonomous science to interpret their observations to guide exploration. In this research we have created a robot able to select science features, direct instruments, collect observations, build maps, and interpret this information to plan actions. We report on field experiments in California's Amboy Crater lava field and demonstrate fundamental capabilities for adaptive exploration in geologic mapping tasks. We show feature detection and instrument visual servoing that enables automated science observation of dozens of targets. Gaussian process models are used to discover spatial and cross-sensor structure including correlations between different locations and sensing scales. The rover develops these relationships on the fly with only on-board computation, reinterpreting remote sensing data in light of the surface materials it observes. The rover learns spatial models of physical phenomena and guides its exploration into informative areas using Maximum Entropy Sampling to improve exploration efficiency. The Amboy Crater experiments show that science autonomy can play a useful role in facilitating geologic survey on kilometer scales.**

I. Introduction

Today's planetary exploration robots do not travel beyond what they observed in the distance yesterday. Advances in autonomous navigation [4,8] and science [1,5,7] permit single-command surveys of multiple kilometers [12] and this portends future planetary rovers that travel over the horizon to survey terrain beyond what has yet been seen. Over-the-horizon operation allows rovers to characterize large areas [6], visiting multiple geologic units on a single command cycle [2]. This will accelerate our scientific understanding of Mars and the other planetary bodies of our solar system.

Communication with these rover will remain intermittent and limited and, as a result, much of the terrain they visit will never be seen by scientists. Onboard science data analysis and planning, which we term *science-on-the-fly*, offers several benefits. These benefits apply to the planets but also to survey on Earth including of the sea floor.[13] First it can play an important role during instrument deployment.[9] Many instruments require precise targeting and calibration which precludes scripted observations [3]. Autonomy that aids target selection and confirms proper placement and the resultant measurement is needed to ensure the quality of scientific information. Next science autonomy helps rovers decide which locations to visit—awareness of scientific value enables them to adapt their exploration strategy on the fly in response to unanticipated trends and anomalies.[10] They can concentrate on informative areas and bypass redundant measurements. This efficiency is paramount since over-the-horizon traverses operate under strict time constraints and must characterize potentially large areas using few samples. Finally science-on-the-fly, enables rovers to summarize their observations and choose most informative samples for downlink over bandwidth-restricted communication channels. [11]

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Fig. 1. Robotic explorer, Zoë, in the Amboy Crater lava field. Stereo cameras enable obstacle detection and terrain modeling for navigation. Additional high-resolution cameras and visible/near-infrared spectrometer collect measurements of rocks and soil for classification and geologic mapping.

This work investigates science autonomy in the context of a geologic survey at Amboy Crater, California (Fig 1.) Our experiments demonstrate data acquisition including automatic feature detection and pointing of a visible/near-infrared spectrometer to measure rock and soil reflectance properties. The result is a representative collection of reflectance spectra from the survey area. The rover averages one rock measured per two minutes of rover travel time.

Next the experiment progresses from individual features to understanding and characterizing the environment as a whole. Our approach interprets spectra, using principal component analysis, to learn a Gaussian process spatial model, or map, of the environment. It leverages this map to make informative navigation decisions that are sensitive to discovered correlations across different locations and sensors. Optimal data collection actions are selected with

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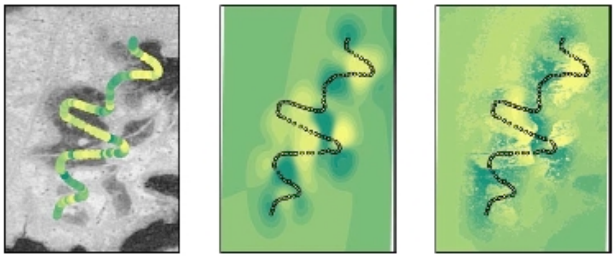

Fig 2. Spectra collected along a traverse classified basalt (yellow) and soil (green), at left, probabilistic classification of geologic type (at center), and surficial geologic map (at right).

Maximum Entropy Sampling to maximize an experimental design criterion: the expected information gain with respect to the spatial model. The agent pursues this objective subject to cost penalties for collecting data or hard constraints on the time available. Developing maps are used to identify high value features for opportunistic data collection and to guide the rover adaptively toward informative areas. (Fig 2.) This method reinterprets surface and orbital data onboard the rover, extrapolating to predict future measurements and replanning its exploration for maximum efficiency. These models let the explorer robot construct kilometer-scale geologic maps of surface material. At the end of the command cycle the map itself proves a valuable data product: it summarizes hundreds or thousands of features in a highly compressed representation.

II. Video Narrative

"*Robots exploring distant planets can communicate only intermittently and must wait for instructions from Earth. Future planetary rovers will explore on their own and plan actions between communication opportunities. They will conduct science surveys, interpreting their observations and adapting their investigation on the fly.*

Zoë is a mobile robot, developed at Carnegie Mellon University, that is capable of autonomous site survey on kilometer scales. Experiments in California's Amboy Crater lava fields have demonstrated several new technologies for autonomous science, including (1) Detection and targeting of science features (2) Classification of geologic types, and (3) Autonomous site survey that creates maps and identifies measurements that provide the greatest scientific value.

As Zoë travels, vision algorithms interpret camera images to find features of geologic interest. Zoë matches these features, which are predominately rocks, across image sequences in order to recognize those rocks that it has seen before. It computes each rock's position and adds it to a catalog of features, their locations and attributes. Attributes such as color, shape, and texture can then be used to classify feature types.

A visible to near infrared spectrometer measures reflectance in multiple wavelengths. Zoë aims its spectrometer using a visual servoing procedure to track rocks up to five meters away. Principal component analysis on spectra strength is used to interpret spectra and draw geologic distinctions.

Zoë is capable of long distance autonomous navigation using stereo cameras to model terrain to identify obstacles, build maps, and choose routes. Science autonomy algorithms exploit these terrain models and rock classifications to guide adaptive exploration. Zoë evaluates the scientific importance of new observations relative to data it has already collected. It can choose informative sites based on the correlations and anomalies it discovers.

Zoë learns the relationships between surface measurements and satellite images. It locates spatial trends such as boundaries between geologic areas and extrapolates to predict future observations. The algorithm dynamically infers a map from spectrometer measurements and prior orbital imagery. The rover replans its survey path on the fly, reacting to obstacles or guiding exploration into areas it predicts will be most informative. It continually adjusts its path to maximize its survey within the time allotted.

Techniques drawn from information theory select the most informative subset of science observations, classifications and maps to communicate back to Earth.

Science on the fly promises a new kind of remote investigation that pairs the expertise of human scientists with science-aware robot explorers. Advances in robot intelligence are creating new opportunities and mission scenarios for planetary science and exploration."

III. Conclusion

Science on the fly is an important capability for robotic explorers that must act autonomously because of intermittent and limited communication. This work visibly demonstrates capabilities for autonomous navigation, feature detection, instrument observation, mapping and exploration to create geologic maps over large areas.

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