TOOLBOX FOR RESEARCH AND EXPLORATION (TREX): ROBOTIC DECISION MAKING IN A FINE-GRAINED ENVIRONMENT.

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Introduction: The Toolbox for Research and Exploration (TREX) is a NASA SSERVI (Solar System Exploration Research Virtual Institute) node. TREX (trex.psi.edu) aims to decrease risk to future missions, specifically to the Moon, the Martian moons, and near-Earth asteroids, by improving mission success and assuring the safety of astronauts, their instruments, and spacecraft. TREX studies will focus on characteristics of the particulate surfaces of these target bodies - the spectral characteristics of fine particles and the potential resources (*e.g.,* extractable volatiles) they may harbor; as well as automated exploration of these surfaces. TREX studies are organized into four Themes (lab studies, Moon studies, small bodies studies, and field work). Here, we discuss plans for field studies, which will focus on improving science yield by delegating mission planning, data collection, analysis, and decision-making to an automated robotic explorer.

Background: Robotic systems play a crucial role in the exploration of Solar System bodies, and will certainly play a central role in future exploration activities. Today's robotic exploration is centered around a tight operator/robot iterative process in which a team of operators carefully instructs the robot on navigation and target selection. Data rates are low and hence a complete assessment of the field area is rare. Activities are therefore decided upon based on expert, albeit limited knowledge of the site. As the robot returns limited data, scientists and operators reinterpret the measurements, gain more contextual knowledge of the environment, make decisions for the next set of activities, and send new commands for the robot to perform.

We posit that the description of the activities to be conducted should not be uniquely prescribed by each iteration of commands sent from the operator, but should be open-ended and responsive to ongoing observations, even without iterative feedback from an operator. The robotic explorers of the future should be able to make decisions regarding which observations to perform in order to address the driving hypotheses with little to no input from an outside operator. Periodically, or when the robotic explorer encounters something that falls outside the realm of expected observables, the robotic explorer would contact the operator to offer updates or request new directions. Our approach transforms the co-robotic relationship from one in which the scientist/operator team plots a path or defines a set of activities into a collaboration in which the human and robot work together.

Technical Approach: In the Tasks associated with this Theme, we will integrate a combination of tools under development by different projects, with the overall goal of advancing techniques in autonomous field exploration and sample selection.

Task 1. Hypothesis map: We envision astronaut/robot field investigations to consist of an iterative process that begins with the formulation of a hypothesis map, followed by the measurement of observables to address the specific hypotheses. The hypothesis map, which represents the basis for decision making and reporting undertaken by the robot, describes a set of hypotheses to be explored (*e.g.*, the geologic history of a field site), and observables that allow these hypotheses to be weighted (*e.g.*, mineralogical composition, as constrained by spectral measurements). As the rover queries the terrain, certain hypotheses become weighted toward greater likelihood, as others are eliminated. In conjunction, the rover populates an n-dimensional parameter space of the observables, allowing it to identify the spatial distribution of compositional (spectral) endmembers, which can subsequently be targeted for in-depth analysis. Communication with an operator is performed at points in which the rover has a) a summary of observations of the mapping area, b) identified sample collection sites, or c) performed an observation that cannot be fit into the hypothesis map. If the latter occurs, the hypothesis map needs to be reformulated, leading to an iterative process between hypothesis formulation and field exploration (Fig. 1).

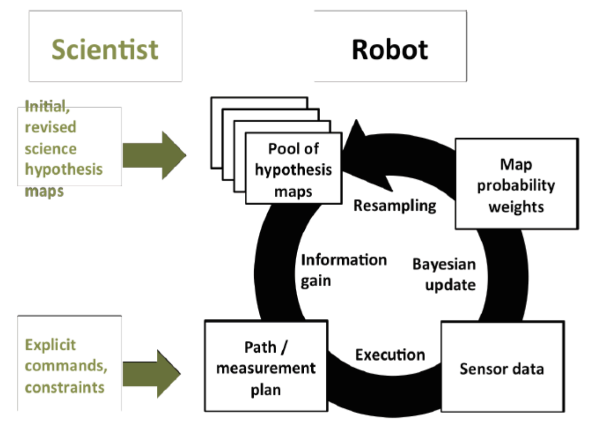

Figure 1. High-level Scientist/Robot exploration flowchart. Scientists can provide input to the robot at multiple stages, from a pool of hypothesis maps to explicit commands, allowing for flexbility in exploration.

We emphasize two primary benefits of this formulation. First, science hypothesis maps improve operations efficiency. Hypothesis maps communicate the latest objectives simply and intuitively, and define the appropriate behaviors. The second benefit is increased science yield. Hypothesis-driven interactions force exploration to be set by quantitative, formal hypotheses that are related mathematically to the measurements made by the robot. In current operations, such hypotheses are often left implicit or only heuristically tied to the activities selected. Quantification of hypotheses and their relationship to raw data leads to a provably beneficial experimental design with direct traceability to mission objectives. This also allows the system to react to unanticipated events that occur while the robot is out of touch with the users [1].

Task 2. Automated spectral analysis: To accomplish the hypothesis testing, the rover must be capable of deriving mineralogy from observed spectra. We will use the Tetracorder software to analyze spectra using multiple algorithms commanded by an expert system. The expert system can make identifications and decisions, and based on those results, apply new algorithms to make additional identifications and decisions. Tetracorder has been central to dozens of studies on Earth and other planets and moons [2-9]. A Tetracorder module operating in real-time on the rover's computer will allow the rover to constrain mineralogy and address the hypotheses it is tasked to test.

Task 3. Strategy development: Incorporating both the hypothesis map and Tetracorder algorithms into the rover will increase science yield and efficiency, and will allow us to explore the different scenarios across which a rover can address the hypothesis map via automated exploration. Scientists will initially create the hypothesis map using remote sensing data. We will then attempt various degrees of communication and command between the scientist and the rover in the field, ranging from 100% automation, to step-by-step commanding by the scientist. We will determine the range of communication latencies that represent the "sweet spot" where the combination of science yield and efficiency can be maximized. Comparisons will be made with that of actual geological work by humans. As part of the hypothesis testing routine, locations for sample selection and collection will be identified by the rover. Once the rover has identified a location for sample collection, it will notify the scientist, who will make the final decision.

The robot must reliably point, control and calibrate the instrument, and validate the acquired data. These functions have been developed [10-11], demonstrating the robotic control required to manipulate a reflectance spectrometer in the field.

Task 4. UV exploration: We will incorporate UV spectral capabilities to the field investigation. The UV wavelength region (~110-400 nm) contains a potential wealth of information about planetary surface materials. Previous work [2; 12-14] has shown that this region is sensitive to different mineral properties than longer wavelengths. The inclusion of a UV spectrometer on a rover or lander on an airless body has the potential to provide critical geologic information about the surface by extending the spectral range that typical field spectrometers sample (e.g, ASD; 350-2500 nm) down to ~110 nm and adding, for example, complementary information regarding iron-bearing phases that may be present.

Task 5. Field Campaign: The objectives of our field investigations are to test the accuracy of our autonomous selection software and UV field spectrometer, and to compare the science yield of current robotic exploration strategies with that of the semi-autonomous robotic exploration system described in Task 1. Fieldwork will be performed at small body analog sites containing fine-grained materials analogous to those expected on asteroids and the Moon. Two locations have been chosen: the Palouse glacial loess site in Washington and the phyllosilicate-bearing Hopi Volcanic Field in Arizona. Multiple instruments will be used during the field campaigns, including three spectrometers (UV, VNIR, FTIR), a gamma ray / neutron spectrometer with active interrogation (GNS), and a Raman spectrometer. These data (UV, XRD, GNS, and VNIR) will be the inputs for our Tetracorder autonomous decision making. The mineral and elemental data will provide a complete picture of the physical and chemical mineralogy of the surface.

Anticipated results and products: • Application of data and results from the other TREX Themes [15-17] into field studies • advancement of hypothesis map software for autonomous sample selection • further development of Tetracorder for autonomous compositional identification • UV field measurements.

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