Robot Science Autonomy in the Atacama Desert and Beyond

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***Abstract*—Science-guided autonomy augments rovers with reasoning to make observations and take actions related to the objectives of scientific exploration. When rovers can directly interpret instrument measurements then scientific goals can inform and adapt ongoing navigation decisions. These autonomous explorers will make better scientific observations and collect massive, accurate datasets. In current astrobiology studies in the Atacama Desert we are applying algorithms for science autonomy to choose effective observations and measurements. Rovers are able to decide when and where to take follow-up actions that deepen scientific understanding. These techniques apply to planetary rovers, which we can illustrate with algorithms now used by Mars rovers and by discussing future missions.**

I. Introduction

Current terrestrial and planetary rovers utilize on-board scientific instruments to provide a breadth of perception far beyond cameras and lasers typically found in mobile robots. Reflectance spectroscopy, including multispectral and hyperspectral imaging, offers a powerful new capability for robot autonomy. Much of what we know about the geology of planetary bodies including the Earth involves interpreting patterns of reflected sunlight at multiple wavelengths. Spectroscopy reveals detailed atmospheric constituents and compositional information: it has discovered water on the Moon [1], and water-formed outcrops on Mars [2]. Orbital imaging spectrometers typically have resolutions of many meters. This means that sub-pixel signals can go undetected. Increasing resolution requires surface observation. There is a need for ground exploration strategies to augment remote observations with direct spectroscopic measurements.

II. Robotic Autonomy

Recent advances in robotic autonomy–particularly long autonomous traverse–will be transformative to these survey and monitoring applications. Rovers can now travel kilometers per single uplink/downlink communications cycle. [3] These robots can survey vast areas. We envision onboard autonomy for *spatio-spectral exploration* in which scientists define high-level measurement objectives and rovers realize these goals by navigating the environment and opportunistically deploying instruments. Autonomous robotic survey will validate and refine the orbital picture without tedious monitoring or extensive low-latency communication.

Figure 1. Typical terrain in the Atacama Desert of Chile presents many opportunities for scientific measurement and observation directly before the explorer, visible in the distance, and possible at long range.

In this research we are designing autonomous systems that perform long-range surveys with the robot acting as proxy to realize high-level science objectives. As it explores, the robot must react to opportunistic discoveries while respecting the limits on available time and energy. It must interpret collected data and balance the information gain of new observations against energy expenditure and mobility hazards. This requires reasoning about navigation and science data collection tradeoffs. Our method is to augment geometric navigational data with additional sensing modalities. (Fig. 2)

In each command cycle the human scientist directs the robot with new goals. These goals necessarily go beyond simple waypoint following

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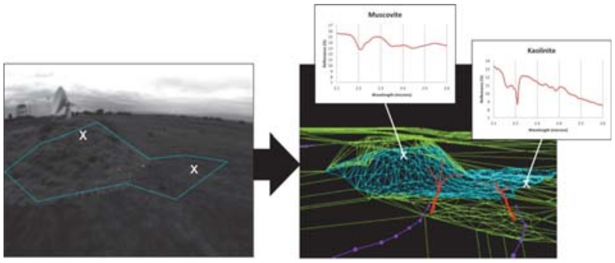

Figure 2. Concept illustration. An explorer robot collects range data for navigation (cyan polygon) and multiple reflectance spectra (X symbols). It estimates a 3-D terrain mesh augmented with spectral data with reflectance at many wavelengths. This allows the explorer to predict navigability and composition. The robot plans paths and science measurements that balance information gain against mobility, energy and time

and scripted data collection, like the command sequences used by current Mars rovers. Instead, the protocol should specify high-level science goals in a language that is flexible enough to accommodate many potential objectives such as searching for a specific subtle target feature, cataloguing different unique materials that are present [4] or refining ambiguous orbital images [5]. Often these science objectives are elegantly expressed as classical experimental design tasks.

We are developing this exploration concept for current astrobiologic studies in the Atacama Desert of northern Chile.

III. Science Autonomy

We are developing several component technologies to enable autonomous spatio-spectral exploration. First, it is important that the rover autonomously acquire good-quality data. This involves selecting candidate science targets and then directing measurement of them.

To this end, we have developed image analysis approaches that reliably detect targets such as rocks as well as more complex structures such as

Figure 3. Rover autonomy can exploit orbital data to plan informative paths. The path, overlaid on orbital image, is the fixed-length circuit that best reconstructs of the remote image. Open circles represent planned acquisitions of reflectance spectra. This path provides "optimal ground truthing" and is recomputed on the fly as new spectra are collected

outcrop and layers [7,8]. This provides the necessary detection capabilities to identify and respond to spectral targets of opportunity. Machine learning strategies, such as random forest pixel classification, are well suited to detect dust and fracture-free surfaces for good quality reflectance spectra.

Second, Instrument management, specifically reliable automatic pointing, control, calibration and data validation is also crucial. We have developed each of these functions [8], demonstrating the robotic control required to manipulate a reflectance spectrometer in the field.

Finally, our research seeks to adapt navigation to serve science. On-board path planners can incorporate remote sensing data to select informative paths. Figure 3 shows one simulation using remote imaging spectroscopy by the AVIRIS instrument [9]. Here each pixel represents a full spectrum of data in visual to infrared wavelengths from 0.4-2.5 microns. The planner strives to accumulate a library of spectra that best reconstructs the entire orbital image, subject to a path cost budget. Adaptive navigation provides more diverse and representative spectra, improving reconstruction by 35% relative to navigation-only path. We are refining these techniques for use in biogeologic mapping in the Atacama desert.

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