Field Experiments in Robotic Subsurface Science with Long Duration Autonomy

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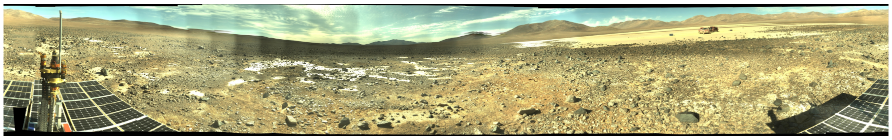

Fig. 1: Panorama taken by Zoë in the Atacama Desert showing the heterogeneous nature of the environment

Abstract A next challenge in planetary exploration involves probing the subsurface to understand composition, to search for volatiles like water ice, or to seek evidence of life. The Mars rover missions have scraped the surface of Mars and cored rocks to make ground breaking discoveries. Many believe that the chance of finding evidence of life is expected to increase by going deeper. Deploying a system that probes the subsurface brings its own challenges and to that end, we designed, built and field tested an autonomous robot that can collect subsurface samples using a 1m drill. The drill operation, sample transfer, and sample analysis are all automated. The robot also navigates kilometers autonomously while making decisions about scientific measurements. The system is designed to execute multi-day science plans, stopping and resuming operation as necessary. This paper describes the robot and science instruments and lessons from designing and operating such a system.

1 Introduction

The search for life in the far reaches of the solar-system compels the use of robots to explore faster, cheaper, and safer than humans. Still these robotic systems and their operations are complex, so it is necessary to practice and test robotic missions on

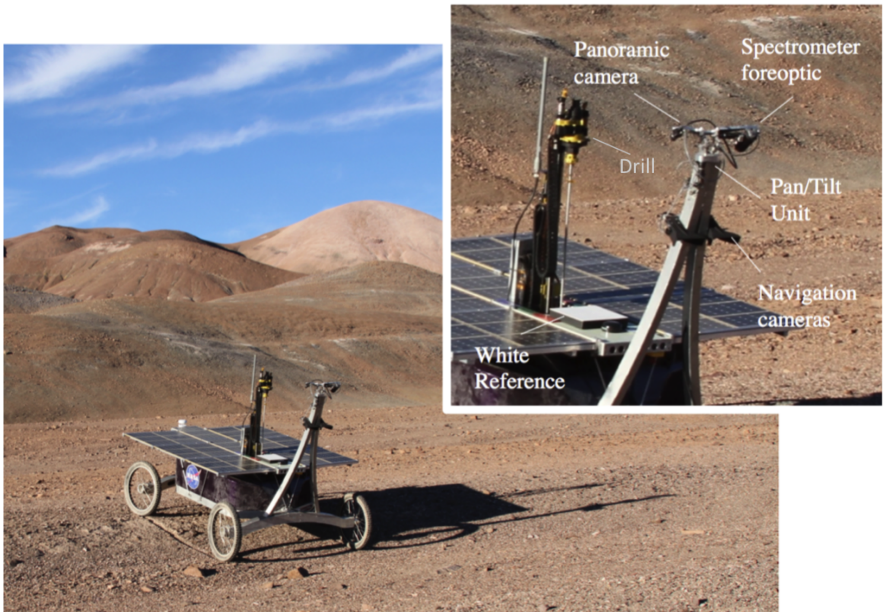

Fig. 2: Zoë

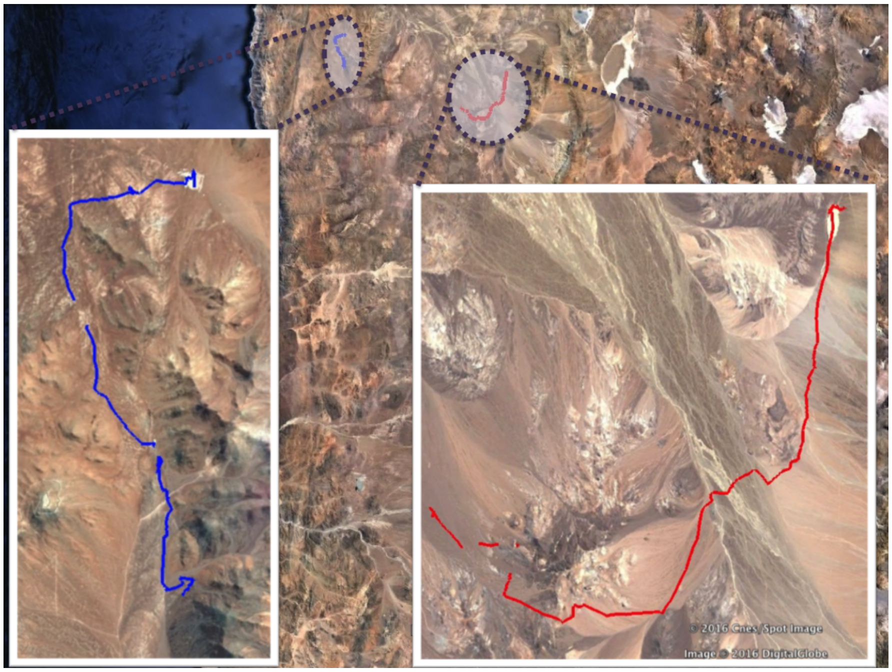

Fig. 3: Region traversed by Zoë in 2013 (red) and 2015 (blue)

Earth to gain insights into the technical challenges and best methods. To that end, we deployed a robotic system and operated it in the Mars-analog Atacama Desert in Chile where evidence suggests that the interior is the most arid and lifeless region on Earth (Fig. 1). Our field investigation uses a rover to make controlled transects in the desert with instruments to characterize subsurface habitats. Figure 3 shows the regions explored in two field seasons to accomplish the following goals:

- **Subsurface sample analysis:** drill into the surface autonomously, collect samples and analyze them using the onboard science payload.
- **Autonomous science sequences:** select sampling targets that maximize the information gain while minimizing the navigational cost.
- **Multi-day autonomy:** operate on a plan autonomously for multiple days: executing commands during the day, detecting the end of day, shutting down the robot gracefully, waking up the next morning and resuming the plan after the robot is fully charged.

The paper is organized as follows. Section 2 categorizes the related work based on our goals. Section 3 gives an account of the robot and its science payload. Sections 4, 6 and 5 details progress with respect to project goals. Section 7 discusses the lessons learned during the field operations.

2 Related Work

2.1 Subsurface Sample Analysis

The Mars Exploration Rovers Spirit and Opportunity landed on Mars in January 2004 carried the Rock Abrasion Tool (RAT) [1] for grinding and brushing. It drilled 0.045 m wide by 0.005 m deep holes in Martian rocks. The Curiosity rover which landed in November 2011 carried a percussion drill capable of drilling 0.016 m wide and up to 0.05 m deep holes [2].

There are few simulation missions similar to our work. The Mars Astrobiology Research and Technology Experiment (MARTE) [3] conducted a drilling operation simulating a Mars mission in 2005. It collected core samples near the Rio Tinto river (southwest Spain). It drilled 6m deep in a 30 day mission and collected 21 core samples. Scarab [4] simulated a lunar mission with a coring drill capable of drilling 1m in Mauna Kea in Hawaii. It processed the core samples and analyzed the composition of captured soil. The Icebreaker mission simulated a Mars polar mission operating the Icebreaker drill [5] in the Arctic and the Antarctic Dry Valleys. The Icebreaker drill is a 1m class drill with a triple redundant sample transfer mechanism which is capable of drilling 1m in 1 hour with approximately 100W of power. However in all these missions, the drilling procedure and the sample handling and analysis procedures were tele-operated manually.

2.2 Autonomous Science Sequences

Eariler works of Thompson et al. [6] fused images from different views of the robot to detect rocks that could be sampled autonomously. This was followed by [7] where the features of geologic interest were automatically detected using a probabilistic fusion technique. Smith et al.[8] proposed different modes of operation for science autonomy and reported qualitative results using Zoë [9].

2.3 Multi-day Autonomy

Wettergreen et al. used Hyperion [10] with goals of long duration autonomy. Given a command, the mission planner generated waypoints which the robot followed autonomously with the health monitor looking for faults. It introduced the basic software structure to operate autonomously for long durations. This was followed by the work on DepthX [11] which was capable of executing an elaborate plan. The missions involved diving into flooded sinkholes in Sistema Zacatón (Mexico), searching science worthy targets, collecting samples and surfacing, all without any telemetry. The plan also included an extensive list of contingency plans for safety. The missions lasted 4 to 6 hours, thus extending the hands-off autonomous operation duration. Scarab [4] extended this capability by including a drilling operation along with the navigation goals. One of these systems have the capability to operate on a plan of possibly unlimited duration and diurnal hibernation.

3 System Overview

The system deployed for the Atacama field experiments is a rover with integrated 1m drill, sample collection and handling to Raman spectrometer and fluorescence imager. Long range sensing with visible-near infrared spectrometer aid in sample selection.

3.1 Rover

We refurbished and reconfigured Zoë [9] to incorporate a drill and scientific instruments for field investigations in June 2013 and March 2015. Zoë is a solar powered robot with passive steering and passive suspension. The solar panels use triple junction GaAs cells $2.4m^2$ with 23% efficiency[12]. It has a pan-and-tilt unit that points a visible near-infrared spectrometer with 1°resolution and a high-resolution camera for taking close-up context images and panoramas.

Zoë has a stereo camera pair mounted on the mast used for navigation. However software is added to use those cameras for science autonomy tasks as well.

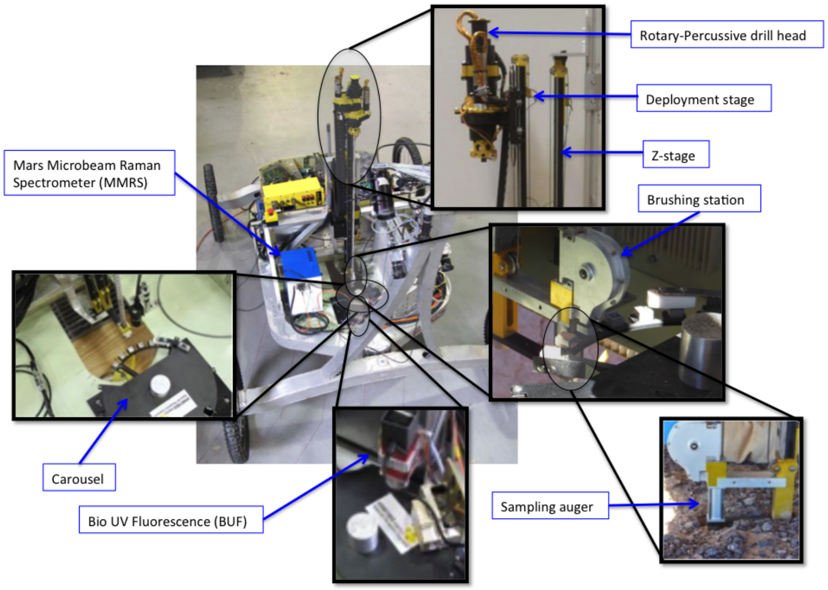

Fig. 4: Zoë with drill and science payload (MMRS and BUF imager)

3.2 Drill

The drill is a two stage, rotary percussive mechanism capable of drilling up to 1m deep. Its design accounts for flight constraints like weight and volume. It weighs 10 kg and consumes 300 W of power on average. The drill is designed and developed by *Honeybee Robotics Spacecraft Mechanisms Corporation* and consists of the following subsystems: *(1) Rotary-Percussive drill head, (2) Sampling auger, (3) Brushing station, (4) Z-stage, (5) Deployment stage (6) Carousel*. (Fig.4).

The drill head is designed with rotation and percussion decoupled. This allows use of the more energy intensive percussive system only when required (e.g., to penetrate harder formations). Both rotary and percussive motors are approximately 150 W each. To reduce sample handling complexity, the drill auger is designed to capture drill cuttings as opposed to cores. High sampling efficiency is possible through a dual design of the auger. The lower section of the auger has deep and low pitch flutes. This geometry creates natural cavities ideal for retaining granular materials (cuttings and soil). The upper section of the auger moves the cuttings out of the hole efficiently.

The drill mechanism lowers to contact with the ground surface with its first stage and stabilize the mechanism on the drill hole. The rotary-percussive second stage then drives the auger into the ground. The mechanism is co-designed with the rover mast for efficient integration and greater overall rigidity and stabilization. For sample collection, soil from the tip of the auger is captured in a collar which expels upon drill retraction down a chute into the sample cups. The carousel is a single degree of freedom system designed to move 20 cups underneath the drop off spout and the other science payload instruments. It has a cantilevered (fully passive) scraper that smooths out and compacts the top powder in each cup. Automatic coordination onboard the rover places specific cups beneath the chute which are then rotated into sealed storage.

The drill uses a *bite* sampling approach where samples are captured in $\sim$ 10 cm intervals. That is, after drilling 10 cm, the auger with the sample is pulled out of the hole, and the sample is brushed off into one cubic centimeter cups by a passive brush within the brushing station. An advantage of the *bite* sampling approach is that stratigraphy is preserved and the provenance depth of the sample is known.

3.3 Mars Microbeam Raman Spectrometer

The Mars Microbeam Raman Spectrometer (MMRS) measures the Raman scattering of the collected samples using a focused laser beam. Raman scattering probes the fundamental vibrations of molecules that produces finger-print spectral patterns with sharp no-overlapping peaks. Laser Raman spectroscopy is a powerful technique for the detection and characterization, at fine-scale, of the major, minor and trace species in a mixture (rocks and soils).

The carousel delivers the samples collected at different depths (10, 30 and 80 cm) under the MMRS probe head. It then collects the Raman spectra for the sample in the sample cup by focusing a 532 nm laser beam. A stepper motor within the probe moves the optical bench linearly over the sample surface in a range of 10 mm, from which Raman spectra of 20 to 100 spots are collected without using autofocus.

The wavelength of the laser used in the MMRS is calibrated using a Ne lamp before, during and after the field experiments. In addition, we measure Raman spectra of substances like naphthalene and diamond which has strong and distinct Raman spectra and use as reference and measure multiple times in a day. This helps us to keep the laser wavelength calibrated and also evaluate the general performance such as sensitivity, noise levels and spectral resolution of the device.

3.4 Bio UV Fluorescence Imager

The Bio UV Fluorescence (BUF) imager shines UV and white light on the samples and measures fluorescence, if any. Fluorescence under UV light is a strong indicator of chlorophyll in the sample which provides evidence of life. 370 nm wavelength UV light LEDs are used in the BUF imager. The imager is a light-field camera manufactured by Lytro, Inc. One unique feature of the light-field camera is that it uses a lenslet array to simultaneously collect a number of images at slightly different perspective with no moving parts. These images comprise a *rayfield image* that can be re-focused after the fact. While this synthetic autofocus feature is not required to examine the flattened powdered samples presented to it in the carousel, this feature enables the BUF imager to examine unprepared rock samples in other venues without the need for a mechanical autofocus mechanism. The BUF imager is controlled by the MMRS which in turn is commanded from the rover computer. The BUF imager is mounted on the same carousel next to the MMRS.

3.5 Visible-Near Infrared Spectrometer and Panoramic Imager

The Visible-Near Infrared (VNIR) spectrometer on Zoë is an Advanced Spectral Devices (ASD) FieldSpec Pro with readings in the Visible-Near Infrared (350 nm to 2500 nm) range. It uses a one-degree foreoptic mounted on a pan/tilt unit alongside the panoramic imager on the mast. Visible/near-infrared spectroscopy involves studying the reflectance spectra of a material in the visible/ near-infrared wavelength range. The goal of the visible/near-infrared spectrometer is to support the rover and other instruments with mineralogical composition information. This can be used to help direct the rover when used in conjunction with orbital based spectral data and to determine locations of interest to the rover.

The Visible-Near Infrared Spectrometer (VNIR) was deployed successfully in the 2004 and 2005 LITA field investigations [13]. However software functionality is added to enable intelligent and complex workflows using the spectrometer. For instance, software functionality is added to calibrate the spectrometer to the camera so that its viewpoint within the image is known and the target of the spectrometer can be identified. Further, several algorithms for detecting features in the panoramic image have been developed and ported to the rover so that it can automatically identify salient features in the scene and then direct and record high resolution image and VNIR spectra.

4 Subsurface Sample Analysis

Drilling: Drilling in consolidated, fine grained soils is easy and the sample is retained in the auger successfully every time. Poorly consolidated, coarse-grained soil, is relatively easy to drill, but capturing and retaining of samples within the auger flutes is difficult. In most cases, the soil is pushed aside as the drill is lowered into the ground and in turn no soil is captured because of low friction angle and lack of cohesion. To address these issues we experimented with various combinations of the following: (1) We increased the diameter of the auger from 0.5 inches to 0.75 inches to enable greater sampling volume (2) We used shallower flutes to help with sample retention, (3) We optimized drilling software to shorten the sampling time, and (4) We drilled without percussion and retracted the drill without rotation. In all cases, the average drilling power is less than 15 W because the percussive system is not needed and hence not engaged most of the time. The weight-on-bit is also low, at 50 N or less. Table-1 lists the different locations we drilled successfully in March 2015 and their depths.

Locale	Latitude	Longitude	Drill Depths(cm)
12	24°29'23.69"S	70°08'52.05"W	10, 15
13	24°29'15.65"S	70°08'52.25"W	10, 19, 50
14	24°29'06.11"S	70°08'52.96"W	10, 20
15	24°29'03.13"S	70°08'53.43"W	10, 17
18	24°29'17.26"S	70°09'02.26"W	10, 15, 20, 50
19	24°29'18.18"S	70°09'04.85"W	20
20	24°29'31.32"S	70°09'59.09"W	20
24	24°34'15.63"S	70°09'31.02"W	10, 20

Table 1: Lists the sites where we successfully completed the drilling operation in March 2015 and their respective depths

A drilling sequence which involved drilling to 10 cm, retracting and dumping to a cup on the carousel, followed by drilling to 30 cm and 80 cm, took a total of 130 minutes. But the duration and sample collection efficiency depended largely on the drilled location and material drilled into.

Raman Spectras:

Any changes, especially the optical alignment of MMRS affected by mechanical, optical or electronic fluctuations during the transverse of the rover, are apparent in the reference spectra. Despite Zoë's 50 km transverse on a rough terrain and a wide diurnal temperature cycle, from -6 °C to 27 °C, during the field campaign, the MMRS did not show noticeable performance change. We did notice the laser wavelength shift, due to insufficient temperature control in the laser unit within MMRS which was later corrected.

Multi-point Raman spectra were obtained for 31 samples. The spectral analysis showed the presence of three groups of minerals in the Atacama samples. They are: original igneous minerals (mainly feldspar and quartz); alteration products (e.g., TiO_2 and goethite); and hydrous or anhydrous salts (sulfates and carbonates) with variable origins.

Bio UV Fluorescence: The BUF imager recorded images of the samples illuminated under UV light. Abundances were negligible, so no fluorescence was detected but images were still useful when the samples were illuminated under white light as they served as a reference for the MMRS measurements.

Autonomy: The system accomplished end-to-end operation collecting samples to analyzing them, several times. This involved drilling to a specified depth, followed by retraction and dumping to a cup on the carousel, moving the carousel to position the cup under the MMRS, recording the Raman spectra, repositioning the cup under the BUF imager, collecting images with UV and white light illuminations and then navigating to a different location. We found that batch processing the samples with MMRS and BUF is much more efficient that processing them individually after they are collected.

5 Autonomous Science Sequences

Zoë's science autonomy system includes two basic capabilities that operates the robot on mesoscale and macroscale features respectively. *Smart targeting* identifies science features in rover navigation imagery and uses this information to point the VNIR-ASD spectrometer. *Adaptive path planning* navigates on scales of tens or hundreds of meters, using satellite images to select waypoints with distinctive or novel spectra. A more detailed account of these techiniques can be obtained from Wettergreen et al. [14].

Smart Targeting[15],[16]: Zoë began each autonomous target selection process by acquiring a navigation camera image. Onboard image processing then analyzed the scene to find large contiguous regions (using connected components analysis) of a desired terrain class (using random forest classification). Typically these classes were rough surface features like rock outcrop or bright sediment patches with distinctive spectral signatures. Upon finding a feasible target, the rover re- calibrated its VNIR-ASD spectrometer, pointed at the feature and collected a small 33 raster of spectra centered on the target of interest. For context, it also acquired a high-resolution color image of the scene.

Adaptive Path Planning: The science autonomy system also operates on larger scales of tens or hundreds of meters, where it analyzes satellite data to adjust its traverse path. We model the explored environment using a standard geographic or area mixing model where each measurement is a mixture of a small number of endmember materials. Endmembers' spectra combine in proportion to their physical extent on the surface. In practice there is always residual error separating the reconstruction from the measurement. This is partly attributable to measurement noise, but unless the library is comprehensive there may also be incompleteness errors (e.g. spectral features that are expressed in the observations but not present in the library). A library that reconstructs all spectra well can be said to have explained the scene, and provides insight into the mineral compositions in the remote sensing data. This intuition provides a figure of merit for an adaptive path planning system to select future measurement locations. Zoë's planner selects locations, the measurements at which provide the largest expected reduction in unmixing error. As a consequence, it aims to visit locations that are spectrally distinctive, collecting samples that fully explain the orbital image.

6 Multiday Autonomy

In order to achieve multiday autonomy goals we created a tool called *Rover Commander* for scientists to generate plans for the rover. To enable the rover to power up and power down the devices through commands from the autonomy system, we built the *Power Management and Distribution (PMAD)* system. Finally, to navigate to a desired location autonomously with used *Reliable Autonomous Surface Mobility (RASM)* [17] software.

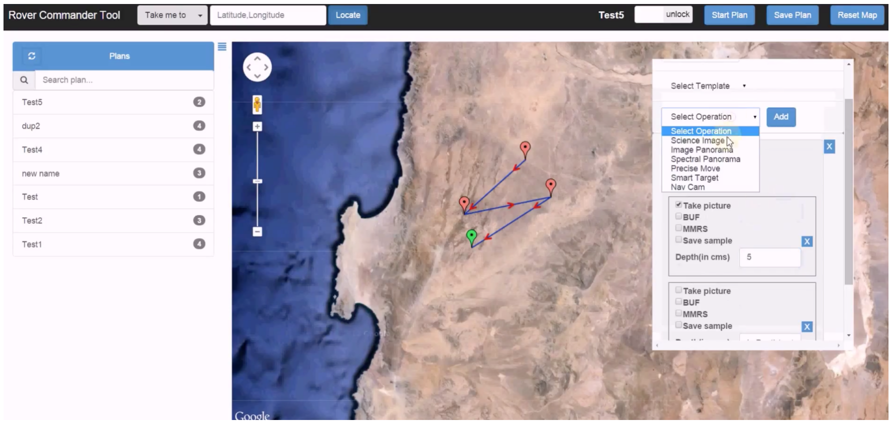

Fig. 5: Rover commander - a web based planning tool to generate science plans for Zoë

Rover Commander: Rover commander is a web-based planning tool that is used to generate a list of commands that can be executed by Zoë. The plan can span multiple days. Fig.5 shows a snapshot of the tool. The tool uses the Google Maps API to source the underlying terrain information. The tool has presets for different operations like drill with different depths, quick or full panoramas, location to move to, drive to location using adaptive science, etc. A sample plan file generated by the

Rover Commander is shown in table. 2.

Command	Description
checkplan	Check plan for syntax error
drill *locale12 500*	Drill command to drill 0.5m and name the sample *locale12*
sotf *-24.488383 -70.151347 0.2*	Use adaptive science (*science-on-the-fly*) to navigate to the specified lat/lon location. Will explore the region while ensuring the additional distance overhead to less than 20%
panorama *-30 30 -20 20*	Generate a panorama with elevation angles (-30°, 30°) and azimuth angles (-20°, 20°)
spanorama *-10 10 -10 10 10 1*	Generate a spectral panorama using the VNIR spectrometer and the high-resolution camera
latlon *-24.488012 -70.150286*	Navigation command to drive to specified latitude and longitude
sotf *-24.486816 -70.148548 0.4*	Use adaptive science (*science-on-the-fly*) to navigate to the specified lat/lon location. Will explore the region while ensuring the additional distance overhead to less than 40%
drill *locale13 300*	Drill command to drill 0.3m and name the sample *locale13*
panorama *-40 40 -20 20*	Generate a panorama with elevation angles (-40°, 40°) and azimuth (-20°, 20°)
spanorama -10 10 -10 10 10 0	Generate a spectral panorama using just the VNIR spectrometer
latlon *-24.487680 -70.147848*	Navigation command to drive to specified location
mmrsbuf	Take MMRS and BUF measurements on all the unprocessed samples (*locale12* and *locale13* in this case)

Table 2: Sample plan generated by Rover Commander.

Operation	Duration (% of uptime)
Science-on-the-fly (adaptive science)	3.20
MMRS and BUF	5.31
Panorama	6.35
VNIR Spectra	9.36
Driving	18.84
Drilling	11.99

Table 3: Percentage of total duration of each of the operations with respect to the uptime

Power Management and Distribution: The PMAD is a low powered embedded computer that is developed to provide a way to turn on/off devices through software. It has solid-state relays connecting to all the devices on the robot which can be controlled through software. This also allowed us to save power on the robot by commanding only the essential devices to be powered up. For example, we powered down the drill and the scientific instruments when driving. Another main utility of the PMAD is to support the idea of surviving the night. When the power goes below a set threshold at sunset, the PMAD sends a hibernate signal to the high-level software which suspends the current plan, shuts down the devices and powers down the robot. In the morning, after the batteries are sufficiently charged from the solar panels, it wakes-up the robot automatically and the high-level software will then resume execution of the previous day's plan.

Reliable Autonomous Surface Mobility: RASM [17] is the onboard navigation software in Zoë that is capable of local hazard avoidance and path planning using a 3D terrain representation.

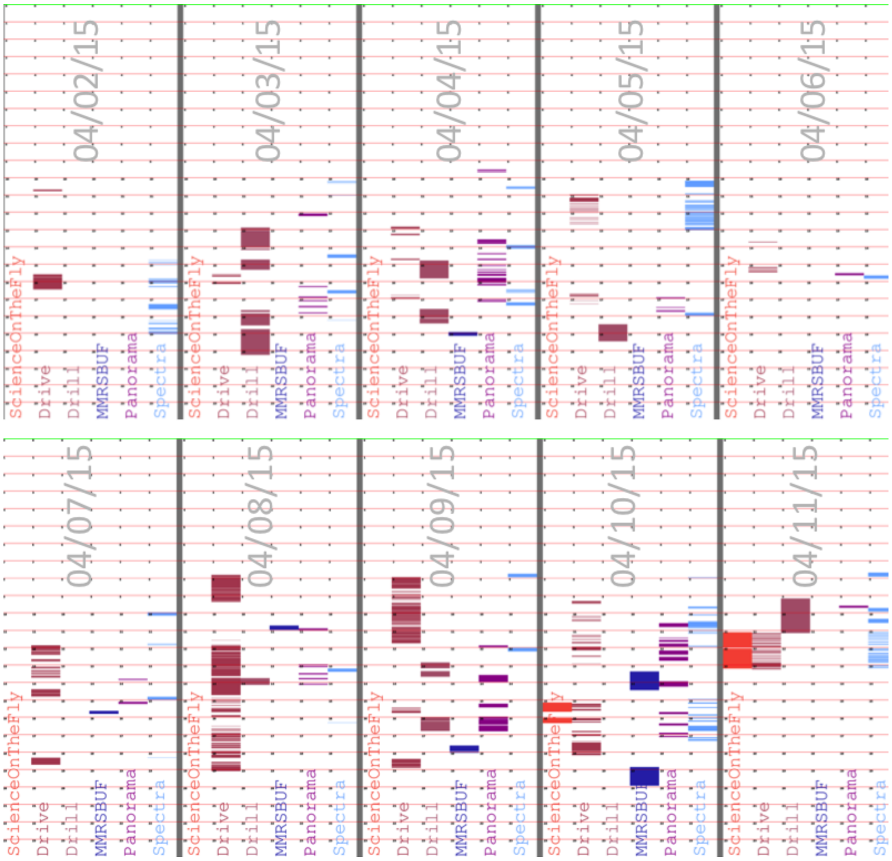

Fig. 6: Graph shows the time of the day each of these operations were performed. Each vertical column corresponds to a day during the field operations and the horizontal rows correspond to the hours in the day.

Autonomy: Zoë demonstrated multi-day autonomy partially. During the end of the day, Zoë suspended the current plan, turned off its devices and hibernated. It survived the night and successfully booted back up the next morning and resumed the previous day's plan from where it left off. But unfortunately for a variety of different reasons, each day of the field season, the motor controllers got into an error state and the robot was not able to accomplish its complete plan but it moved a few meters before encountering the error state thus demonstrating the capability but not accomplishing it.

Table-3 shows the percentage of time each of the specific operation was carried out compared to the uptime of the robot. Fig. 6 shows the time of the day when these operations were performed. Of all the operations, driving took the most amount of time. This is because we drove *25.6 kms* in 10 days. *60.62%* of the total distance was driven autonomously in these exploration experiments.

7 Lessons Learned

- **Drilling in unconsolidated soil:** After digging and inspecting a pit, we noticed many layers of different soil combined with layers of rocks and void spaces. The possible explanation for not being able to generate sample in the cup may be the collapse of material into the void spaces, as evidence by the lack of tailings pile at some sites.
- **Time/power for MMRS:** The MMRS instrument consumed more power than that could be sourced by the solar panels. This is because the laser was designed to be operated on the cooler environment in Mars. Also each measurement took more than a few minutes which added up as the number of samples increased.
- **Fiddling with science plan:** Although the robot had the capability to continue executing a plan for several days, the plan was often modified multiple times. This was mainly because the scientist found value in altering the plan when the robot arrived at a new locale. This was also common due to the fact that the Atacama desert received historic rains during our field investigations and the environment was changing drastically.
- **Registration of orbital data (salar experiment):** We used the data from ASTER satellite for the orbital data. However we found that the ASTER images are misregistered. This prevented the science autonomy software from accurately guiding the rover in some cases.
- **Software integration eariler, rather than modularity:** We favored modularity and delayed the integration of the different software components. But we learned, once again, that integrating the software components early in the development process saves time.
- **Use a standard tool for logging:** Early in the software design we decided to use SQL based logger as opposed to a custom binary logging tool. It proved useful as it is hard to maintain a custom logging tool for several years. However since our data is logged into a SQL database we can use any SQL tool to access the data. This greatly aided data analysis.

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