

SECOND EXPERIMENTS IN THE ROBOTIC INVESTIGATION OF LIFE IN THE ATACAMA DESERT OF CHILE

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ABSTRACT

The Atacama Desert of northern Chile may be the most lifeless place on Earth, yet microorganisms do survive in some areas. The distribution and diversity of life in the Atacama remains unexplored and is the focus of the Life in the Atacama project. To conduct this investigation, survey traverses across the desert with biologic and geologic instruments will allow us to create biogeographic maps. We accomplish these surveys with an autonomous astrobiology rover.

In this paper we motivate the Life in the Atacama project and report on the second of three field seasons of scientific investigation and technical experiments in Chile. We describe the rover, instruments, algorithms and assess intermediate results. These results provide insight into the design of an effective robotic astrobiologist for future planetary investigations and into the best methods to conduct astrobiologic surveys.

1 INTRODUCTION

The Atacama Desert is the most arid region on Earth and in several ways analogous to Mars. It has been suggested that the interior of the desert is the most lifeless place on Earth—we are examining this hypothesis—yet it is known that microorganisms exist on rocks and in soils where the desert meets the Pacific coastal range. The distribution and diversity of life and habitats in the Atacama's subregions remains unexplored.

A mobile robot makes the measurement of the distribution and diversity possible. Mobility is crucial as habitats are hypothesized to depend on locally variable conditions including moisture, solar flux, and rock/soil composition. The ability to traverse tens to hundreds of kilometers while deploying sensors to survey geologic and biologic properties of the environment is a fundamental requirement because only by visiting many sites will the few in which organisms exist be found.

The Life in the Atacama (LITA) project is investigating life in the desert and the habitats in which it survives. In our first field season (2003) we found that microhabitats, on the scale of a few meters or tens of meters, were sparsely distributed in coastal regions and were detectable by fluorescent and spectral signatures. In this, the second season (2004) we revisited the coastal region and also investigated the existence and character of habitats in the desert core.

Our goal is to make genuine discoveries about the limits of life on Earth and to generate knowledge about

life in extreme environments that can be applied to future planetary missions. Through these experiments we also hope to develop and practice the methods by which a rover might best be employed to survey desert terrain and seek evidence of life.

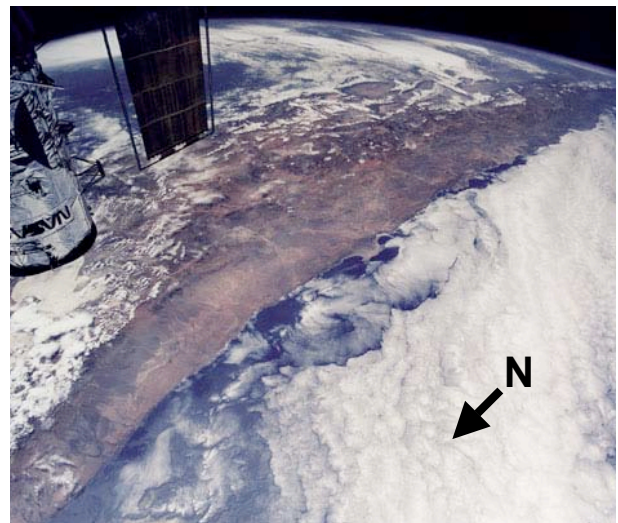


Fig. 1. Atacama Desert from the Space Shuttle (Hubble in foreground). The desert is cloudless with moisture restrained by the Andes to the east and the Antarctic current flowing north up the coast.

1.1 Atacama Desert

The Atacama Desert in northern Chile lies between the Pacific coastal range and the Andes. (Fig. 1.) It is drier even than the Antarctic plateau, for in some regions there has been no measurable precipitation in decades. Along the west coast, fogs, called camanchacas, occasionally penetrate through the coastal mountain range and reach the desert to produce condensing moisture measured in fractions of a millimeter. In the east snowmelt from the Andes feeds an aquifer deep below the desert. (Fig. 2.) Lakes can form in areas where the groundwater surfaces although today with the receding water table most are dry salt beds: salars.

Site-specific studies have found organisms in varying concentrations in some areas of the Atacama. The distribution of these organisms and the boundary conditions for each habitat remain unknown.

1.2 Terrestrial Mars Analogue

The Atacama Desert presents an excellent analogue to Mars because it is extremely dry but also, like Mars,

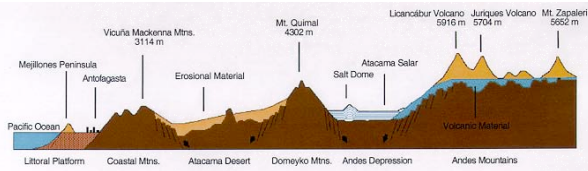


Fig. 2 Profile of northern Chile (facing north). LITA is studying terrain from the eastern slopes of the coastal mountains through the core desert to the western slopes of the Domeyko Mountains.

the desert experiences high ultraviolet radiation because altitude (up to 4000 m above sea level) and atmospheric transparency due to the lack of water vapor. A relative humidity of only 5% is not unusual. The soils in the Atacama have been found to be particularly high in oxidants, which leads to the rapid breakdown of organic material. [1] A similar discovery was made by the Viking landers in their analysis of Martian soil. [2] The result is that in some regions of desert almost no biogenic material can be found despite the continuous atmospheric infall that occurs globally.

For these reasons: aridity, ultraviolet radiation and soil composition we believe the Atacama is analogous to Mars. Of course, the Atacama is not uniform or constant in these properties. There is variation in aridity between the central desert and its boundaries along the coast and altiplano, solar insolation varies with season and altitude, and the composition of the soil is determined by local mineralogical context. The study of life in the Atacama tells us more about living organisms and their adaptation to this extreme environment here on Earth as well as potential habitats or at least areas for investigation on Mars.

LITA opens the way to a new generation of rover missions that advance from the general study of habitability, for example by seeking evidence of water as the Mars Exploration Rovers have succeeded in doing, to the upcoming search for, and specific study of, habitats and life on Mars past and possibly present. The LITA science payload reflects this transition by combining complementary elements, some directed towards remote sensing of the environment (geology, morphology, mineralogy, climate) for the detection of conditions favorable to terrestrial life and some directed toward the *in situ* detection of life's signatures (biological and physical, such as biological constructs and patterns). The payload is designed to both detect organic biomarkers and chlorophyll-based life and to characterize habitats. The existence of endoliths in extreme environments similar to early Mars makes the testing of detection methods for chlorophyll-based life a valid working hypothesis. Whether or not life on Mars (if any) used—or uses—photosynthesis, detecting its signature will likely involve accessing isolated oases scattered over large distances. LITA is demonstrating this capability in a relevant terrestrial analogue.

1.3 First Field Investigation

In our first field season, we tested component robotics technologies and modified Hyperion, a solar-powered rover that was designed to exploit the advantages of sun-synchrony in polar regions. [3] We transformed the rover for an equatorial desert environment by

reorienting its solar array to horizontal after numerical analysis of insolation (solar energy) indicated that for unbiased direction of travel, a horizontal orientation would produce highest output. We tested this quick prototype and to determine the necessary requirements for a terrestrial life-seeking rover. That has led to the rover configuration for the second field season.

In year one we also prototyped and evaluated three instruments: a stereo panoramic imager (SPI), a visible-to-near-infrared spectrometer (VNIRS) and an imager capable of detecting mineral and biologic fluorescence.

We formulated the concept of rover survey traverse and designed the rover navigation algorithms so that the rover could achieve several kilometers of traverse per day. [4] We also developed the methods and procedures by which remote scientists would utilize a rover capable of multi-kilometer daily travel. This change in approach from detailed observation with minimal mobility to quick survey with maximal distance traveled supported science goals but required new thinking about how to plan and prioritize science.

The result of the first field season is that all tests indicate that it is feasible to deploy the necessary biologic and geologic instruments with a rover and to successfully detect life and characterize habitat. The detection of life was not accomplished unambiguously but indications are that with appropriate instruments and rover it would be possible.

1.4 Objectives

While the first field experiments validated components and methods and the second validated the functional integration of the necessary devices and capabilities for exploration. This represents progress towards the LITA objectives in areas of science and technology (Table 1.) and advances to the final season when we anticipate a fully operational science investigation.

Table 1. Research Objectives and Significance

Objective	Significance
Seek life	Establish if the hyper arid region of the Atacama represents an absolute limit to life and understand the gradient of biodiversity and environments
Understand Habitat	Understand the strategies used by life to survive in arid environment following climate changes
Apply Relevant Science	Design a payload able of confirm environments for life and test science exploration strategies enabling the positive identification of life
Over-the-Horizon Navigation	Exhibit productivity of traverse achieving 1km per command cycle
Efficient Resource Utilization	Enable science rovers to reason about resources and make on-the-fly decisions to optimize productivity
Autonomy and Self-awareness	Engage science rovers in telescience, managing with minimal communication, while fully aware of themselves and their surroundings

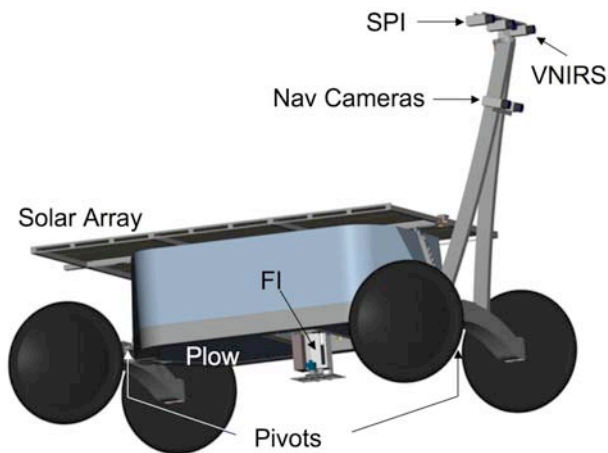


Fig. 3. Zoë rover has four driven wheels and passive pivots attaching the axles to the frame. Body roll is averaged between the axles by a spine that supports the solar array. (Plow is shown stowed.)

The combined intent and significance of our objectives is to deploy actual life-detection instruments with a rover capable of long-distance traverse in an extreme environment were important questions about the nature of life remain unanswered. We intend to answer some of those questions and to do so by creating a first robotic astrobiologist.

2 ASTROBIOLOGY ROVER

We have developed a rover capable of the payload capacity, precise motion, power efficiency, energy capacity, rate of progress, slope-climbing ability, and overall endurance required for the Atacama science investigation. This configuration we have named Zoë, the Greek word for “life”.

2.1 Requirements Analysis

To support the intended investigation, we identified the following issues with and modifications to the Hyperion mechanical and electrical configuration [4]:

- Accommodate science instrument payload
- Incorporate translation motions for imager
- Increase solar array power output
- Increase battery capacity for low-light operations
- Increase computation for more complex planning
- Add low power and switched electronics
- Increase rover speed to decrease traverse time
- Increase wheel torque to improve slope climbing
- Eliminate drivetrain hysteresis to improve control
- Incorporate subsurface access mechanism

2.2 Rover Configuration

The Zoë rover configuration addresses these requirements while maintaining many of the desirable configuration properties and roughly the same dimensions at 1.63 m width and 2.0 m length. With the instrument payload the mass has grown to 198 kg.

Like the original configuration, Zoë has independently driven wheels but it now has two passively articulated axles where previously the rear axle was fixed to the body. Each axle is attached to the chassis by joints that are free to rotate in two degrees-of-freedom (roll and yaw). A linkage between the axles averages the rolling

angles to provide smooth motion to the payload. This linkage also acts as the spine to which the solar array is affixed. (Fig. 3.)

The axle roll motion allows the wheels to follow the terrain. A motion control algorithm adjusts wheel speeds to steer (yaw) the axles in the desired direction. [5] Specifically each wheel velocity must be coordinated not only to propel the vehicle but also to articulate the chassis and put it in the proper configuration for the desired steering action. Predictive feed-forward and precise feedback control minimize wheel slip and skid. This mechanism is not skid steered; the wheels continually articulate the chassis and propel it smoothly forward (or backward since it is symmetric). Although Zoë cannot turn in place steering both the front and rear axles, turning radii as tight as 2.5 m can be achieved. The maximum velocity is 0.9 m/s (3.2KPH).

Zoë is solar powered through an array of triple-junction gallium-arsenide cells that provide, on average, 23% efficiency in converting solar energy. The 2.4 m² array powers a 72 volt bus. The bus voltage is maintained by two 1500Whr Li-Polymer batteries that charge when there is excess power and are drawn down when energy is needed, either from low production (sunlight) or high consumption, as when climbing slopes.

2.3 Mobility

The Zoë configuration has not yet undergone the extensive mobility tests that were applied to Hyperion, however it is obvious that its performance is superior. This is due to several factors that derive from higher performance 72 volt motors driving the wheels through harmonic gears. The result is triple the torque and speed. In practice Zoë is able to climb whenever tractive force can be generated. (Fig. 4.)

In unconsolidated materials, like sand, loss of traction is a concern and a potential weakness of the dual passive axle configuration—if no traction is available steering is impossible as is case for most vehicles. In the Atacama soft sand is rare but we have seen lateral slipping on loose pebbles. We are investigating software-based slip control to address these conditions.



Fig. 4. Zoë climbing a cross slope in the Atacama Desert. Maximum slope climbing capability reaches the angle of repose of unconsolidated sand, about 30°.

2.4 Sensing and Computing

Zoë incorporates extensive internal sensing both to enable it to operate autonomously and to measure performance for experimental analysis. For example, voltage and current sensors throughout the rover sense power input, storage, and consumption by individual motors, computers, and instruments. Internal temperature is sensed in several areas.

Proprioceptive sensors for estimating motion without relying upon external sources like GPS include encoders on each wheel, potentiometers in all joints, inclinometers to measure body roll and pitch, and a single axis gyro sensing angular rate in yaw.

Zoë has eight cameras on a Firewire bus, three incorporated in the SPI, two for obstacle detection, two viewing the area under the body, and one for tracking the sun (to provide an absolute heading reference).

Zoë has four general purpose processors: two Pentium 4, 2.2 GHz processors for all autonomy, navigation and science functions, one Pentium 3, 700 MHz processor dedicated to sensor sampling and localization, and one AMD SC520, 133MHz for power monitoring.

2.5 Plow

The UV radiation in the Atacama is too strong for many organisms to survive unprotected. Some have developed protective exteriors while others take natural shelter under or within rocks or in the soil. To seek these organisms, we prototyped a plow that deploys from under the rover to expose the shallow subsoil. This plow, which faces rearward, is able to overturn rocks and the top 2 cm of soil in a 30 cm swath that aligns with the rover's underbody cameras. (Fig. 5.)

The plow was manually deployed this field season and its downward force depends upon a rigid mount. It was successful in clearing material including loose rocks up to 5 kg. After assessment of potential risks, the plow, in addition to being automated, will have a constant load mechanism to apply steady force to the ground and self-recovering breakaway mechanism that will release the blade if it becomes entrapped.



Fig. 5. Plow prototype deployed under the rover overturns the top 2 cm of material as Zoë moves backwards (toward right) to image exposed subsoil that it imaged undisturbed while moving forward.

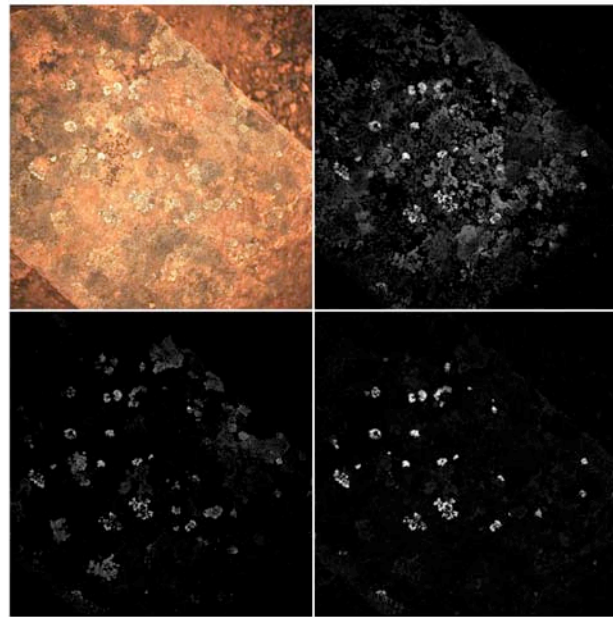


Fig. 6. Images from the FI, composite RGB (upper left), natural chlorophyll fluorescence from 450 nm excitation and 740 nm emission (upper right), protein probe detection from 450 nm excitation and 510 nm emission (lower left), and carbohydrate probe detection from 540 nm excitation and 620 nm detection (lower right). Together corroborating the likely presence of multiple organisms.

3 LIFE-DETECTION INSTRUMENTS

Instruments have been selected for LITA to unambiguously confirm the presence of life. Our approach is to establish multiple confirming lines of evidence by spatially relating observations. The payload includes a daylight Fluorescence Imager (FI) that is fully integrated within the rover, a visible-near infrared spectrometer, and a high-resolution trinocular camera rig.

We tested this instrument payload to learn the best methods of use and technical properties important to deployment by a rover.

3.1 Fluorescence Imager

Fluorescence is the property of some molecules to emit light at longer, lower energy, wavelength than the wavelength that illuminates them; it is caused by the absorption and emission of energy by the electrons composing the molecule. The FI on Zoë can detect fluorescence in daylight under the shade of the rover. This requires band-pass filters and a high sensitivity camera because fluorescence is usually overwhelmed by sunlight. Using 450 nm (blue) or 540 nm (green) excitation and 740 nm (infrared) detection, the natural fluorescence of chlorophyll can be excited and detected. The FI applies a 10 μ sec, 1 J flash so that fluorescent emission is stronger than sunlight at 740 nm. (Fig. 6.) Color images are created by imaging with 630 nm (red), 535 nm (green), and 470 nm (blue) band-pass filters with full-spectrum illumination from the underbody flash lamp.

Other organic molecules can be induced to fluoresce by the application of dye probes that only fluoresce when they bind to the target molecule, like a specific protein or carbohydrate. Amino acids and lipids can also be detected with dye probes. The FI is used to localize chlorophyll-bearing organisms and with fluorescent dyes, the presence of carbohydrates and proteins.

3.2 Visible/Near Infrared Spectrometer

The wavelengths of light reflected and absorbed by surfaces determine the colors we see but when measured more precisely they form a complete spectral signature. A spectrometer measures this irradiance pattern and can be used to identify mineralogical and chemical composition. We have customized and integrated a portable spectrometer, an Analytical Spectral Devices FieldSpec Pro with sensitivity 350-2500 nm. It is internal to the rover but connected by a multi-strand fiber-optic line to a 1° foreoptic mounted on the SPI pan-tilt mechanism. This allows the spectrometer to collect spectra of nearby rocks and soils, or patches of more distant terrain. The composition of the imaged surface determines the spectra, which can be thought of as the convolution of the spectral signatures of the individual components. From a catalog of mineral spectra the ratio of the various components can be estimated. Chlorophyll is one of many compounds with an identifiable signature.

4 NAVIGATIONAL & SCIENCE AUTONOMY

The LITA software architecture, like the rover, has evolved from the Hyperion system that simultaneously addressed resource utilization and navigation. [4] There are three functional groups: mission planning and execution, navigation and control, and science and instrumentation. (Fig. 7.) Our research continues in

resource cognizant planning, over-the-horizon navigation, and rover autonomy with growing emphasis on science autonomy. Science autonomy enables the rover to reason about scientific objectives and make better decisions about instrument application and data validity and selection.

4.1 Navigation Approach

Our navigation approach assumes a realistic planetary exploration scenario in which prior satellite-based mapping is available at scale much greater than the robot, in the Atacama, 30 m resolution. Routes between goals, kilometers apart, can be planned to optimize time and energy requirements. The Mission Planner constructs a search space in location, time, and energy and uses the TEMPEST/ISE search engine to find an optimal solution using the available information. [6] Replanning occurs in real-time as additional information is discovered.

This second year of field experimentation has seen increasingly long and complex plans which require a Rover Executive, developed by NASA Ames Research Center, to execute and monitor.

Zoë moves continuously between goals at an average speed of 0.5 m/s (1.8 KPH), which is clocked by the minimum terrain evaluation rate. Zoë applies near-field stereo vision to detect obstacles by estimating slope, roughness, and continuity of the terrain and evaluates the best path to the goal (at 4 Hz). The Navigator drives 10-15 cm towards the goal and evaluates again.

In order to improve the robustness of the system in cluttered terrain we devised obstacle recovery behaviors that enable Zoë to back up along its prior path when all paths forward are blocked. The Navigator produces reverse commands until a new path

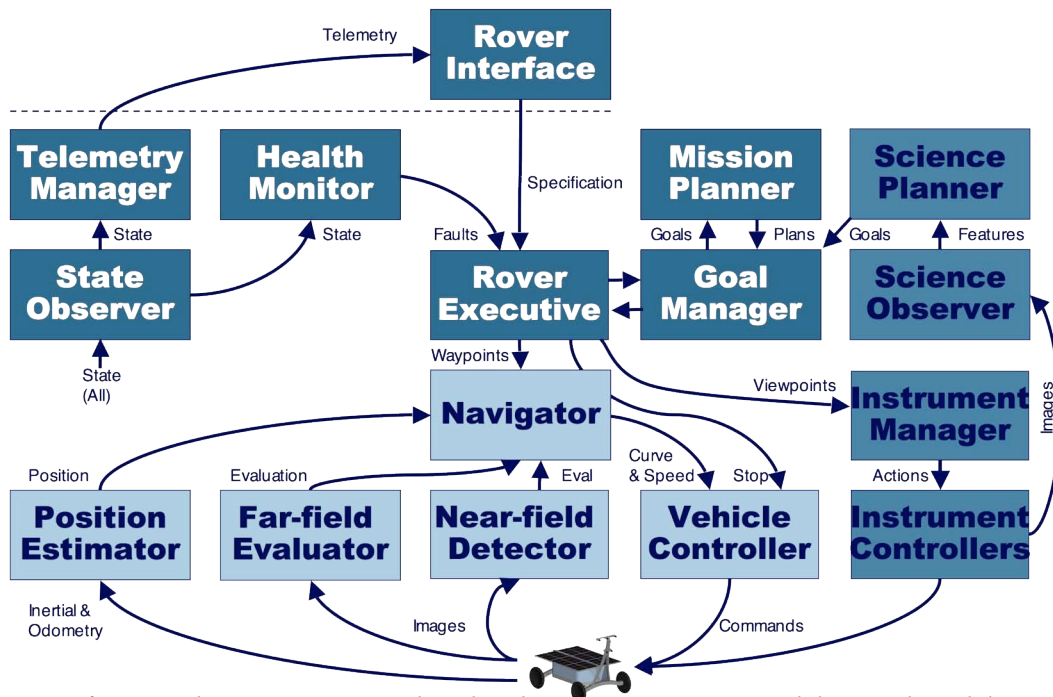


Fig. 7. LITA software architecture is patterned on distributed communicating modules. Each module is a process with one or more threads deployed on the 4 processors onboard Zoë. Command sequences flow from an offboard interface to the Rover Executive which coordinates planning, navigating, and science actions.

forward is detected. If set to never give up the rover will expend much time and energy in complex rubble fields working back and forth until it finds an escape. We observed an instance of 1:2.8 map-to-odometric travel, meaning Zoë drove nearly three times the distance to the goal in order to ultimately reach it.

We continue to investigate far-field sensing and terrain evaluation techniques that will enable rovers to look farther ahead and avoid medium-scale terrain features like hills and drainages and other impassible regions. The multi-scale navigation framework we are developing incorporates satellite-based, far-field, and near-field evaluations in one navigation representation.

4.2 Science Approach

Our approach to scientific investigation of desert habitats is also patterned on a planetary mission. Rover activity is guided by a remote science team reviewing instrument data and rover telemetry at Mars-like data rate and volume, 150Mb per day.

Science goals are determined based on satellite imagery and ground-based observations accumulated by the rover. Operating from Pittsburgh, scientists review the previous days instrument observations to see whether they have confirming evidence of life in each locale visited. They can then decide which area the rover next survey for life. This specification of navigation and science goals is expanded onboard into specific actions with the Instrument Manager directing the function of individual instruments and the assembly of their data products.

We seek to maximize the quality of the scientific data return. Onboard science autonomy modules are being investigated to verify data products, add additional observations, and select particularly interesting observations for transmission. The Science Observer independently analyzes SPI images to classify rock and soil types and produce summary statistics and priority-based data products. It examines FI images to detect fluorescence. It is the function of the Science Planner to decide when these analyses and detections warrant inclusion in daily telemetry or further observations.

Preliminary analysis indicates that, at least, the intelligent analysis is better than random selection. [7]

5 SECOND FIELD INVESTIGATION

The technical experiments conducted in the second field season focused on necessary in situ validation of instruments, algorithms, and models and on the functional integration of the instruments with the rover. Subsequent experiments sought to extend the distance of traverse and quantify termination conditions.

The field investigation involved two sites: Site B, September 2004, is an area of the Atacama near the more humid (20-90%Rh) coast and Site C, October 2004, in the arid core of the desert (3-15%Rh). (Site A was studied in April 2003.) Each site was ground-truthed by an independent science team.

5.1 Coastal Habitat

We explored coastal regions of the Atacama Desert near Salar Grande (Site B) within a few kilometers of the coast on the eastern slope of the range (21°S, 70°W). This region was characterized during pre-mission satellite analysis as having characteristics

including drainages and moisture traps, controls on exposure to solar radiation, and mineralogical composition that could influence the abundance of microorganisms. At Site B teleoperated traverse totalled approximately 6 kms and visited 14 locales.

Hypotheses examined include: possible carbonate signatures in spectroscopy indicative of aqueous activity (evaporates and mineralization); topologically controlled flow of atmospheric water vapor; features associated with surface water flow including hydrogeologic sources; controls on habitability from seasonal variation insolation. Chlorophyll-based organisms including lichens were positively identified at Site B by remote scientists (Fig. 6., previous).

5.2 Interior Desert Habitat

Our interior desert exploration (Site C) occurred at the Buscuñan Hill complex on the western side of the Domeyko Range, which divides the interior from the Andean altiplano (25.2°S, 69.5°W). Again satellite data was used to develop an investigation plan for full science payload examination of 10 locales and traverse of 23 kilometers of which 14 kilometers were eventually completed autonomously. (Non-autonomous traverse did not employ obstacle avoidance or was teleoperated.)

Hypotheses examined include: topologic basins (ponding areas) present enhanced biologic potential; quartz mineralogic signature (in emission spectra) indicates increased potential for hypolithic habitats; limited insolation and increased altitude benefit colonization. At Site C constituent organic molecules (carbohydrates & proteins) were identified at higher abundance than expected. (Fig. 8.) At least one possible hypolithic colony, to be confirmed, was found but almost no chlorophyll.

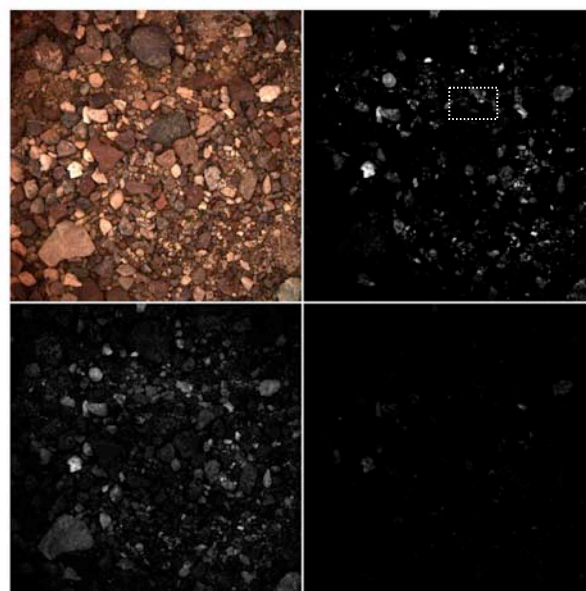


Fig. 8. Images from the FI, composite RGB (upper left), carbohydrate fluorescence (upper right) and protein fluorescence (lower left). Note the minimal background sunlight irradiance in the protein wavelengths (lower right) and the same for carbohydrates. Inset box encircles possible hypolithic (inside rock) organisms.

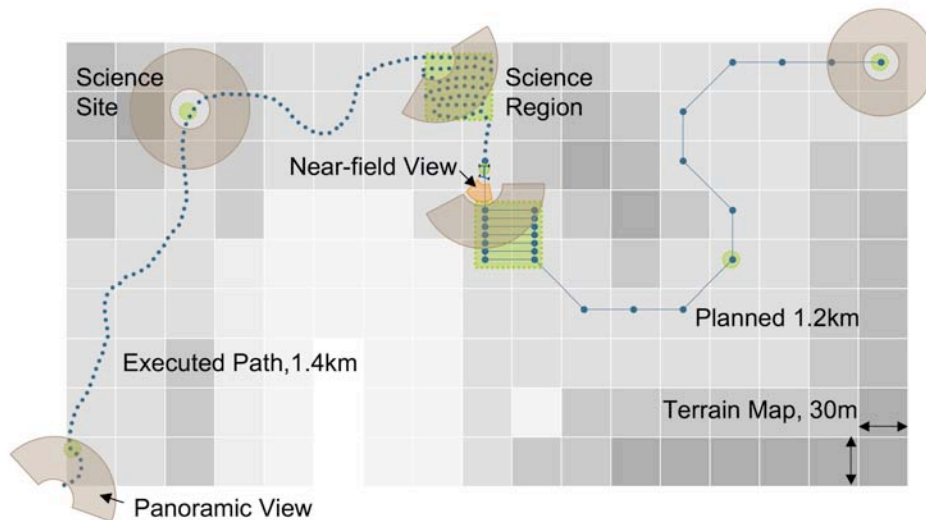


Fig. 9. Survey traverse concept illustrated with rover part way through the execution of a daily traverse that includes visits to 6 science sites, 2 of which involve intensive observations over a region. The plan, based on a 30m satellite elevation model, is for 1.2km of traverse but actual odometric distance will be 10-20% longer.

5.3 Remote Investigation Procedure

An important aspect of this research is the development of a concept of operation for survey traverse. We have formulated our scientific investigation around the hypothesis that to find life in the desert we need to examine many potential habitats. The concept of operation is for daily traverse of 1-2 km that leads to rover between locales in which instrument observations are made. (Fig. 9.)

Proving out this concept has demanded a rover that is relatively fast moving with instruments that can make quick measurements. It must autonomously plan, replan, and execute activities to progress through its survey. If any unresolvable condition occurs, the rover is forced to halt and await new goals the next day. The challenge is to avoid getting stuck and maximize the scientific data return.



Fig. 10. After reviewing daily uplink of data, the remote geologists and biologists plan the next sol's activity. Over 20 scientists participated in 2004.

Each investigation lasts 7 sols (days) including 1 sol for landing site examination and 6 sols for traverse and observation. Before the beginning of the remote investigation, scientists had access to visible and multispectral orbital data (ASTER, IKONOS) with equivalent resolution to current Mars orbiters. Science

operations were conducted with Mars-relevant bandwidth, actual command sequencing, and a cycle of one data uplink and downlink per day. The science team began most days around noon with a review of prior data and drafting of the expected plan for the next sol. After about 6 hours new data from the current sol's activity would arrive and be quickly assessed. As the rover's final location and disposition was determined, the expected plan was assessed in light of the new information. Additional or changed goals and observations were determined and by around midnight the specification of activities for the next day was transmitted to the rover.

5.4 Ethnographic Studies

After our first field season we determined that an important aspect of this research would be a deliberate evaluation of our method of robotic astrobiology. Our basic objective, the unambiguous detection of life and characterization of habitat, had already led to a concept of operation built upon long traverse with periodic scientific observation. We continue to refine that concept and are collaborating with human-robot interaction researchers that are studying how scientists understand and utilize robotic devices and how accurately scientists interpret rover behavior and field measurements. As part of the LITA project our science team is being observed by ethnographers and the ground truth team tests hypothesis formed by these scientists. [8]

Our aim is to not just to simulate a planetary mission by applying similar constraints, but to understand what methods and practices are most effective and scientifically accurate.

5.5 Autonomous Traverse

The culminating experiments this season were carefully recorded autonomous traverses: in total 272 traverses were conducted of which 96 exceeded 150m and 10 exceeded 1km in length. (Fig. 11.) The longest traverse was 3.3km, which required over 100 intermediate waypoints generated by the Mission

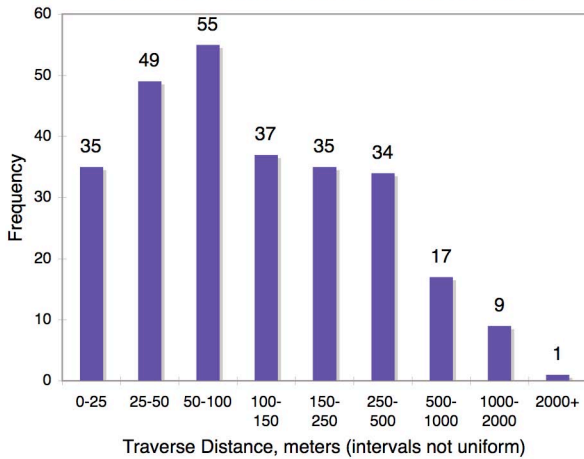


Fig. 11. Autonomous traverse by distance (in 272 commanded traverses conducted in the field).

Planner. Each test was initiated by a single goal sequence uploaded to the rover and concluded when Zoë had reached a termination condition: 45% successfully reached the intended goal and another 25% ended in non-fault conditions (operator error, communication loss, etc.) and 25% ended in a minor fault, typically a software error (stereo vision failure, localization lost, etc.). (Fig. 12.) Potentially fatal faults, meaning those that could not be recovered remotely such as hitting an obstacle or descending an embankment accounted for 5% (14/272) of tests conducted. Zoë navigated autonomously, determining feasible paths and avoiding detected obstacles, for a total of 55 km during the field season.

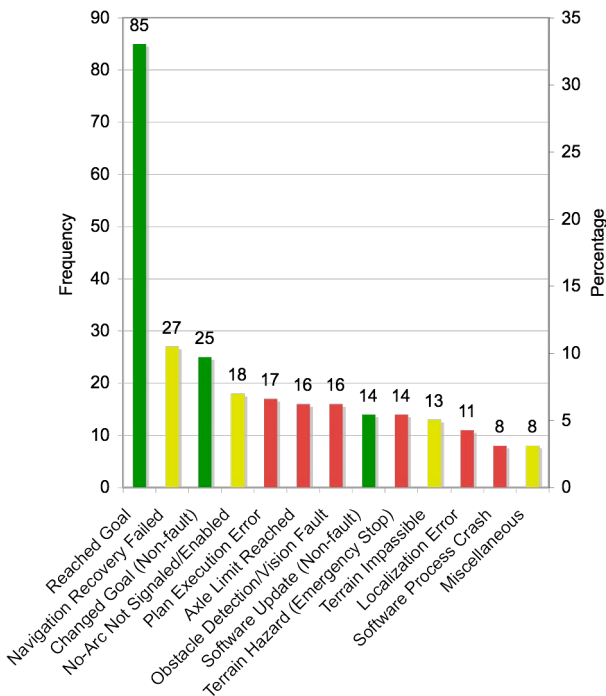


Fig. 12. Termination conditions for 272 autonomous traverses with green indicating success, yellow for faults with known solutions and red needing more involved consideration.

6 CONCLUSIONS

The second field experiments by the Life in the Atacama (LITA) project met their scientific objectives and technical milestones. They resulted in a productive scientific investigation and technical experiments at two sites in the desert. Significant accomplishments include:

- Rover deployment of an instrument for daylight imaging of organic fluorescence
- In situ detection of organisms in coastal and central desert field sites
- Execution of 55 km of autonomous rover traverse with 10 segments over 1 km per command cycle

At this point, we believe that we have developed an instrument payload capable of unambiguously detecting life and a rover able to autonomously conduct survey traverse in desert environments.

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