Long-Distance Autonomous Survey and Mapping in the Robotic Investigation of Life in the Atacama Desert

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Abstract

To study life in the Mars-like Atacama Desert of Chile we have created a robot, Zoë, and conducted three seasons of technical and scientific experiments. We describe Zoë's exploration algorithms and architecture and assess a total of six months of long distance survey traverses. To date Zoë has navigated autonomously over 250 km. Its average distance per autonomous traverse is 672 m with 75 traverses over one kilometer in a single command cycle. Zoë's payload includes instruments to rapidly measure biologic and geologic properties of the environment. By registering these measurements to estimated position scientists are able to correlate biologic, geologic and environmental factors and better understand life and its habitats in the most arid desert on Earth.

Figure 1. Zoë rover in the Atacama Desert during science investigation of micro-organisms in the coastal region.

1. Introduction

Life in the Atacama Desert of northern Chile is sparse overall and distributed in localized habitats on scale of tens to hundreds of meters. Several of these habitats have been studied in detail and have revealed organisms in varying, but minute, concentrations. [1] Today little is known about the distribution of life and extent of habitats across the desert. In particular the boundary conditions for a habitat are not well established. A survey of the abundance of microscopic life and habitat conditions helps to establish a framework for understanding life in the desert.

We conceived an approach to biogeologic mapping by conducting transects across the terrain with both biologic and geologic instruments. We accomplished these surveys in a method that is technologically relevant to Mars exploration using an autonomous astrobiology rover.

Previously we have motivated the scientific investigation of the Life in the Atacama (LITA) project as well as the important analogues to Mars in terms of aridity, high ultraviolet radiation, soil composition and terrain types and appearance. [2, 3] In this paper we focus on our method of long-distance traverse and the accumulated results of three field seasons.

1.1 Long-distance Navigation

Mobile robots can make possible the measurement of the distribution and diversity of life by enabling accurate and efficient survey traverse. 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 or hundreds of kilometers while repeatedly deploying sensors to measure 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.

An implication of the scientific objective for multi-kilometer traverse is that the rover must be able to navigate well beyond its visual horizon. It must navigate in real time because every action cannot be planned with the information about terrain that it has in its initial sensor field of view.

The rover must be able to navigate unknown terrain, detecting and avoiding obstacles over extended distances. Our technical objective is to enable the rover to navigate at least one kilometer in each command cycle. This calls for reliable and robust obstacle detection and avoidance. Every feature that constitutes a barrier to locomotion must be detected and evaluated. For this, the rover will require dense terrain maps on which to perform traversability analysis. It must have models of the vehicle and capability as well as metrics on which to evaluate the cost in time, energy, and risk of traversing a particular path.

We have developed a method for long-distance navigation for planetary rovers and have conducted field experiments to quantify performance.

1.2 Biogeologic Survey

Commonly studies of life in extreme environments focus intensely on the examination of limited samples to provide detailed information about organisms and the habitat at specific locations. Studies of the distribution of organisms provide regional perspective but require many observations drawn from many locations.

By survey we mean, a statistically significant set of repeated observations and measurements distributed over a region. It is biogeologic because observation is of the presence, abundance, and morphology of organisms on rocks and in soil and measurement and estimate geological and mineralogical properties of each locale. Additionally environmental properties are recorded and context imagery is collected.

The biogeologic survey involves a regional transects with repeated, and rapid, assessment of biologic potential and evidence. Rapid because in a traverse of multiple kilometers and dozens of observations, limited time is available to dwell at any one locale. Like any survey we want to conduct an accurate and unambiguous count of key parameters, and that implies a significant sample size.

A biogeologic survey might be conducted in a variety of ways, but we accomplish it with an autonomous robot acting as surrogate for scientists in the field. We intend to establish technologic milestones and demonstrate that biogeologic survey is a viable method of investigation and discovery.

2. Long-Range Desert Rover

The rover configuration must address our requirement to reliably traverse rough desert terrain while also keeping power consumption low. This implies a rugged chassis with adequate drive torque and wheel traction but also low mass and power efficient components and operation.

Table 1. Zoë Rover Specifications

Mass	198 kg
Dimensions	1.63 m width (axles), 2.20 m length (between axles), 1.80 m height 0.35 m ground clearance
Wheels	0.75 m diameter
Turning	2.50 m radius
Speed	0.90 m/s nominal, 1.10 m/s maximum
Power	72 V bus 120 W steady-state + 90-260 W locomotion
Solar	Triple junction, GaAs, 23% efficiency (average), 2.40 m^2
Battery	Lithium-Polymer, 1500 Whr capacity (x2)
Computing	2.2 GHz Intel Pentium4 , 1GB RAM (x2) 700 Mhz Intel Pentium3, 256MB RAM 133 MHz AMD SC520,

The rover we created for this purpose, Zoë, has independently driven wheels and two passively articulated axles. (Figure 1) 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.

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. [4] 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. (Table 1)

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 m^2 array powers a 72 volt bus. The bus voltage is maintained by lithium-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 (climbing slopes).

Zoë incorporates internal sensing both to enable it to operate autonomously and to measure performance for experimental analysis. Voltage and current sensors throughout the rover sense power input, storage, and consumption by individual motors, computers, and instruments. Proprioceptive sensors for estimating motion 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 its pan-tilt mechanism to form a trinocular panoramic imager, two for near-field obstacle detection (navigation), 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 processors for autonomy, navigation and science functions, one processor dedicated to sensor sampling and localization, and one micro-controller for power monitoring.

3. Autonomous Operation

The architecture of the rover software has evolved from an early emphasis on obstacle avoidance and resource monitoring to accommodate the needs of autonomous operation for science survey. Earlier generations of this architecture operated the Hyperion rover which did not have scientific instruments. [5] The Zoë architecture is organized in three functional groups: mission planning and execution, navigation and control, and science and instrumentation. (Fig. 2)

The architecture exhibits a property of sliding autonomy so that the current conditions dictate the robot's degree of autonomy. For experiments in the Atacama we focused on autonomous operation and, as our objectives indicate, long-distance autonomous traverse with automated scientific operation.

In the navigation and control group of components, the Near-field Detector classifies terrain, generating a traversability map from stereo imagery. (Figure 3) The Position Estimator integrates odometry and inertial sensing to estimate rover position and orientation. The Navigator evaluates the map and selects a steering arc that best leads the robot from the current position to the next goal. The steering arc and velocity are commanded to the Vehicle Controller which drives and steers the robot by coordinating the motor servo control. This closes the navigation loop: sense, plan, act. The Health Monitor samples sensors and software variables to detect faults.

Determining where the rover should traverse is determined by scientists who choose areas of exploration and then a Mission Planner determines a energy and terrain feasible routes and produces a scheduled plan, at 30 m resolution. The Rover Executive, developed at NASA Ames Research Center, parcels the plan out to the Navigator as the Health Monitor checks progress. In the event of faults (either physical conditions like low power or erroneous sensor readings, of failures to track the details of the mission plan) the executive can initiate contingency actions or return to the Mission Planner, via a Goal Manager, to re-plan activities and resume progress.

The science autonomy aspects of the architecture are in development and are described elsewhere. [6,7]

3.4 Navigation Components

Our navigation approach assumes a realistic planetary exploration scenario in which prior satellite-based mapping is available at scale greater than the robot (in the Atacama 30 m resolution). Routes between goals, kilometers apart, can be planned to optimize time and energy requirements however obstacles in the near-field (rocks and pits) and far-field (slopes, cliffs, drainages) must be detected and avoided

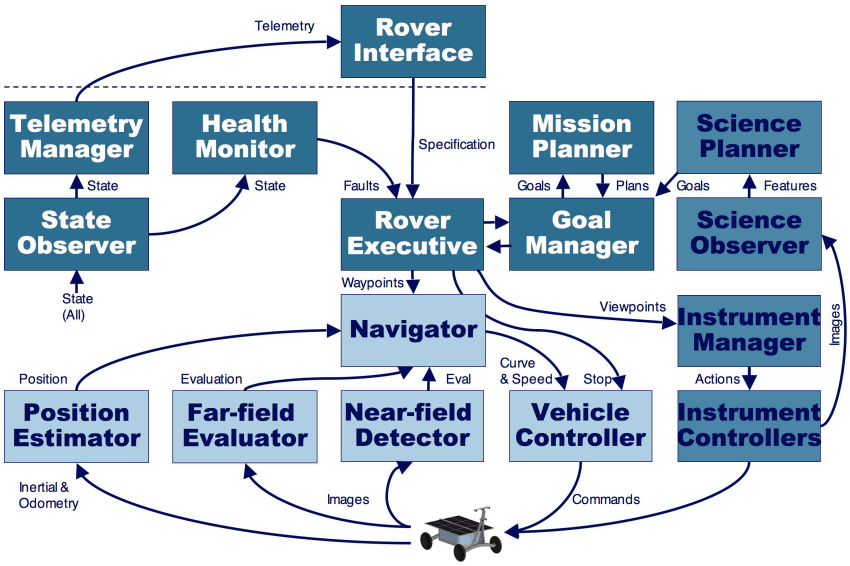

Figure 2. LITA software architecture is patterned on distributed communicating modules. Each module is a process with one or more threads deployed on the 4 processors onboard Zoë.

by the rover in real time. 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. [8] Re-planning occurs in real-time as additional information is discovered. The Mission Planner produces a series of goal locations (waypoints) and times based on its models of the rover and environment and from scientist's survey objectives. It is these waypoints that Zoë's navigation components attempt to reach.

Position Estimator. To navigate, a rover needs to know where it is and be able to estimate its position as it moves. This is crucial for autonomy; if it cannot track position it cannot reach commanded goals and its scientific observations lose their intended targeting.

The precision of rover position estimation must be 5% of distance traveled. At small scale if commanded to move forward 1m, the rover should move at least 95 cm but not more than 105 cm and at larger scale when sent to a region 10 km distant, it should arrive within 500m. For Zoë, this is accomplished with a Kalman filter that incorporates experimentally-tuned vehicle and sensor models with measurements from four wheel encoders, chassis kinematic sensors, inclinometers, and a yaw gyro.

The further implication of the 5% precision requirement is that the rover must estimate its orientation to within 3°. Orientation errors larger than 3° result in cross-track error of greater than 5%. So while it is necessary to have high-precision relative estimates of motion, it is also necessary to maintain high-accuracy estimates of absolute orientation. Zoë's sun tracker is used to estimate absolute heading and to correct for drift in the gyro. [9]

To remain Mars-relevant artificial satellites cannot be used for navigation. Zoë has a GPS receiver that records ground-truth for performance evaluation independent of its position estimate.

Near-field Detector. Zoë uses stereo vision for terrain perception in the near-field (1-7 m). (Figure 3) The nature of planetary terrain encourages the use of an optimistic traversability metric. Terrain not seen by stereo vision, due to weak texture and poor image correlation, is considered traversable for planning. We have found that stereo vision is effective in sparsely-featured natural environments, like the desert. Obstacles tend to reveal themselves as they move closer into range. There is little benefit to avoiding unknown areas. Because obstacles are scarce and almost always distinguishable it is more effective to optimistically treat the unknown as traversable and then rely on stereo to eventually detect any obstacle that does exist.

This strategy works in part because the Near-Field Detector cycles at about 4 Hz or about 10-25 cm of rover travel. Since its near-field extends to about 7 m

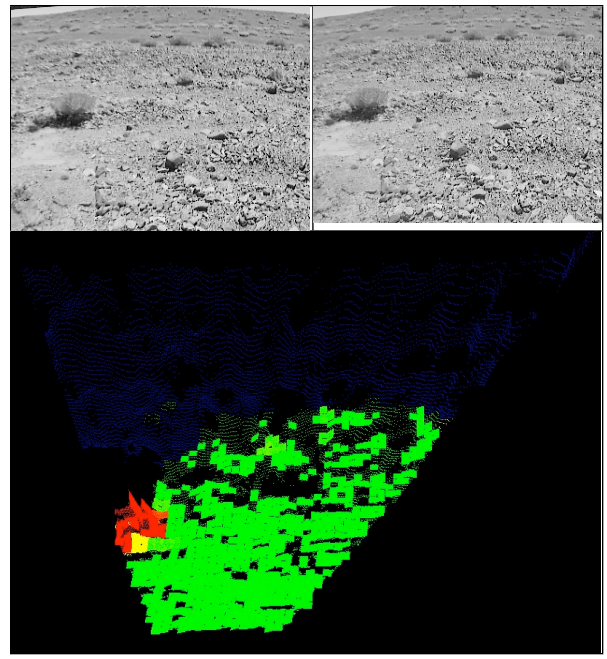

Figure 3. Left and right stereo image from the navigation cameras (above) and the resulting traverability model (below) showing evaluated patches of terrain, their height and orientation.

that means that each terrain patch is evaluated about a dozen times before the rover encounters it and this makes it very likely to detect an obstacle if one exists. In dense obstacle fields where the robot is steering dramatically the maximum lookahead (7 m) may not cover obstacles that appear while turning. However in high turn situations the Navigator reduces rover speed and this has the effect of increasing the number of evaluations of terrain per distance travel. In practice Zoë eventually detects all significant obstacles, meaning those larger than 25 cm.

Navigator. Zoë moves continuously as the Navigator drives the vehicle from one waypoint to the next. For each of waypoint, a new map is initiated and commands are generated to drive the robot. (Figure 4) Path selection is performed on the instantaneous traversability model (from Figure 3). First an initial group of arcs, corresponding to constant steering angles, are evaluated. Next the additional expected cost of travel from the end of the arc to the goal is computed using the D* algorithm [10] and a total cost is assigned. In further refinement the Navigator generates new arcs near the lowest cost arcs and evaluates them. This iterates until no significant refinements occur or time runs out. The Navigator chooses the arc that has the lowest value of total cost and commands the radius and speed to the Vehicle Controller. The rover travels a fraction of the chosen arc, and then the Navigator iterates. As a result of

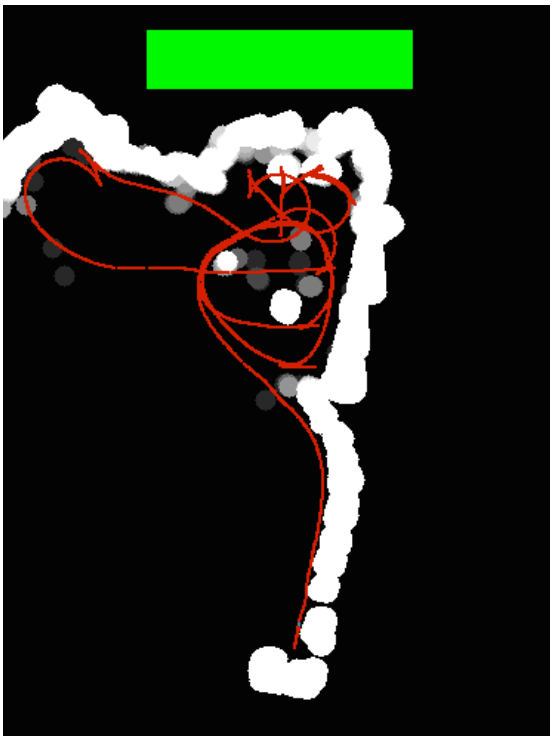

Figure 4. Navigation map from an traverse on a promontory (in Pittsburgh). The goal is the rectangular region at top. Round dots in varying size and shades of grey indicate obstacles. Zoë circles around as it seeks a path down off the promontory to the goal. Note several points where the rover backed up. This pathological case ended when Zoë ran out of time to reach its goal.

rapid updating, smooth transition among discrete arcs is achieved.

In order to improve the robustness of the system in cluttered terrain we devised obstacle recovery behaviors that enable Zoë to back up when all paths forward are blocked. It does not need to look behind it, instead it uses its model of previously evaluated terrain. The Navigator produces reverse commands until a new path forward is detected. As long as time permits the rover will not give up in its search for a traversable path. We have observed up to 1:2.8 map-to-odometric travel, meaning Zoë drove nearly three times the direct distance to the goal in order to reach it.

4. Experimental Process and Results

The LITA project was designed as a three year activity driven by annual field seasons in which we conducted scientific activities for biogeologic survey as well as technology experiments to verify and refine the performance of long-range autonomous navigation. The long-range navigation experiments included much of the science survey but also many other traverses. Careful bookkeeping of every traverse has allowed us to accumulate statistics on over 574 experiments. Our approach was to incrementally built from individual component tests to functionally-integrated navigation to a fully-operational science rover. We established annual metrics to push development. (Table 2)

Table 2. Field Investigation Metrics

Year	Activities	Duration (50% Ops)	Distance	Observations	Location
1	Component Testing	30 days	10+ km	10 Survey Observations	Coastal Range **A**
2	Functional Integration	60 days	50+ km	100 Survey Observations 10 Focused	Coastal Range **B** Hyper Arid **C**
3	Operational Science	100 days	180+km	160+ Survey Observations 16+ Focused	Coastal Range **D** Transition Region **E** Hyper Arid **F**

4.1 Long-distance Traverse

The procedure for conducting navigation experiments was to convey a mission plan to the Rover Executive and engage autonomous operation. Zoë would then begin its traverse and drive until it reached its final waypoint or was unable to recover from a fault or, rarely, if an operator intervention occurred. At all times a field observer was in proximity to the rover to ensure safety. This observer was typically 100-1000 meters away from the rover but in dangerous terrain (meaning near cliffs) they stood 1-10 meters away.

When each traverse ended, either at the goal or for other reasons, the experiment was concluded and statistics recorded. The termination cause for each traverse was determined and categorized.

Component Testing. In our initial proof-of-concept experiments we primarily conducted component-level tests of hardware including sensors, instruments, and actuators. In this first field season we also ran tests of autonomous rover operation and the performance of the entire software system in order to verify the capability and determine specific areas for continued research and experimentation.

Approximately 18 km of traverse was achieved autonomously with the Mission Planner working from a digital elevation model to identify a time/energy minimizing route and the Rover Executive and navigation components acting to drive the rover through terrain. In this manner the rover was frequently able to traverse over 500m before detecting any fault condition Autonomous traverse were executed in 90 experiments. The average distance per traverse during these initial tests was 200 m and the average speed was 0.25m/s. There were 8 traverses that exceeded 300 m and one traverse that exceeded 1 km (1118 m) with a single command. We will not further account these proof-of-concept tests other than to identify our first

instance of 1 km autonomous traverse. Upon their completion the navigation software was substantially improved, the remaining software components came online, and fully integrated tests became possible.

Functional Integration. 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 science instruments with the rover. Autonomous navigation experiments sought to extend the distance of autonomous navigation and establish the capability for survey traverse.

The 2004 field season resulted in carefully recorded autonomous traverses: in total 272 experiments were conducted over 2 months. (Figure 5.) Of these traverses 96 exceeded 150 m and 10 exceeded 1 km in length (ironically 2 more traverses exceeded 995 m). The longest traverse was 3.3km, which required over 100 intermediate waypoints generated by the Mission Planner. Each test was initiated by a single goal sequence uploaded to the rover and concluded when Zoë had reached a termination condition. Termination conditions included the following.

- Reached Goal (success)
- Changed Goal - distant or non-specific final goal specified and experiment concluded when new mission plan was initiated (non-fault)
- Controller Fault - axle reached soft limit, in many cases this fault can be recovered automatically (non-fatal fault)
- Terrain Impassible - medium-scale terrain feature, cliff, drainage, slope, blocks the path (fatal fault)
- Software Update - swapped in improved software and initiating new mission plan (non-fault)
- Executive Fault - the rover executive hung or fault state for which a contingency was unspecified (non-fatal fault)
- Operator Error - either an initial condition/process was not started properly or something was inadvertently interrupted (non-fault)
- Instrument Fault - control level fault of an instrument (non-fatal fault)
- Mechanical Fault - problem with either the pan/tilt or plow (non-fatal fault)
- Localization Error - usually initialization problem but sometimes due to timing or uncorrected gyro drift (non-fatal fault)
- Processor Reboot - spontaneous reboot followed by automatic restart of navigation software (non-fatal fault)
- Vision Fault - failure to produce disparity either from video buss problem or dynamic range issues (high or low light) (non-fatal fault)
- Navigation Fault - failure to find a path (non-fatal fault)
- Battery Fault - low-voltage warning or Li-Ion shutdown (non-fatal fault)
- Miscellaneous - process crash without proximate cause (non-fatal fault)

Of the 272 traverses 45% concluded in success or a non-fault condition (a change of goal). Another 25% could be termed likely-successful traverses in that the fault condition was corrected and the recovery could have been made remotely (stereo vision failure,

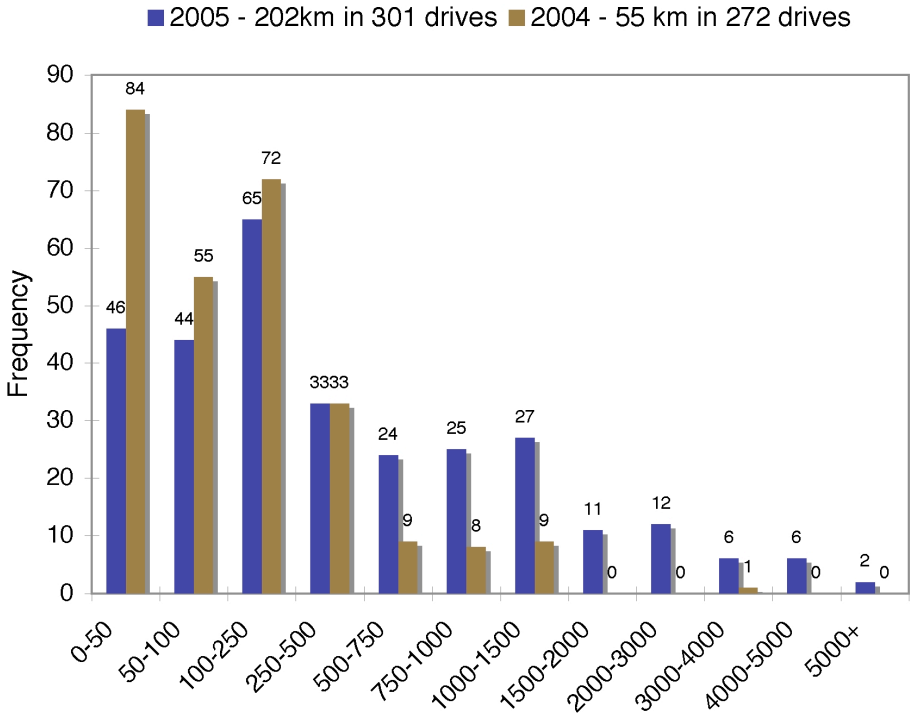

Figure 5. Traverse Distance, meters (intervals not uniform)

localization lost, etc.) with loss of one command/ communication cycle. The next 25% of traverses failed for largely non-navigational faults (operator error, communication loss, etc.). Potentially fatal faults, meaning those that could cause the end of a planetary mission such as hitting an obstacle or descending an embankment accounted for 5% (14/272) of tests conducted in 2004.

Zoë navigated autonomously, determining feasible paths and avoiding detected obstacles, for a total of 55 km during the field season.

Operational Science. In the third field season with instruments integrated and operational on the rover much of the emphasis was on science. Therefore the rover's autonomous driving was intermixed with collecting panoramic imagery, high-resolution close-up images, visible-near infrared spectroscopy and fluorescence imagery of the soil, all controlled automatically by the Rover Executive. Occasionally Zoë would drive to a goal, plow the surface away, deploy its instruments, pack up and drive off to the next science waypoint. Despite the added complexity, the median distance of autonomous traverse increased to 216 m, from 97 m previously; the average distance per traverse tripled to 672m from 208m. The total number of traverses over 1 km was 64. (Figure 5)

Improvements in navigation system dramatically reduced faults in terrain perception and path selection. Overall the careful tracking of faults enabled the team to correct software faults and also push the rover into more difficult terrain. As a result 47% in traverses ended in success, 37% in likely-success, with either a minor fault or at worst the loss of one command cycle. Only 15% of traverse ending faults required intervention. None of these (0/301) were potentially mission ending, although those having to do with instrument or mechanical (pan-tilt unit) would have resulted in loss of some functionality.

Of more than 202 km of autonomous traverse in 2005 nearly half, 94 km, occurred with science activities in the mission plan. Zoë's longest traverse was 6.3 km in a single uninterrupted mission plan.

4.1 Biogeologic Mapping

Biogeologic survey was conducted suring 110 km of autonomous traverse over the duration of the LITA project. The measurements of the abundance and distribution of biogenic material and geologic and environmental properties are spatially correlated as a result of the Zoë's precise localization. Scientists have assembled this data as evidence for their hypotheses about the factors that are controlling the distribution of life in the desert. [11] An example of biogeologic mapping is shown in Figure 7.

5. Conclusion

We have proven robotic capabilities for long-range autonomous traverse and demonstrated biogeologic

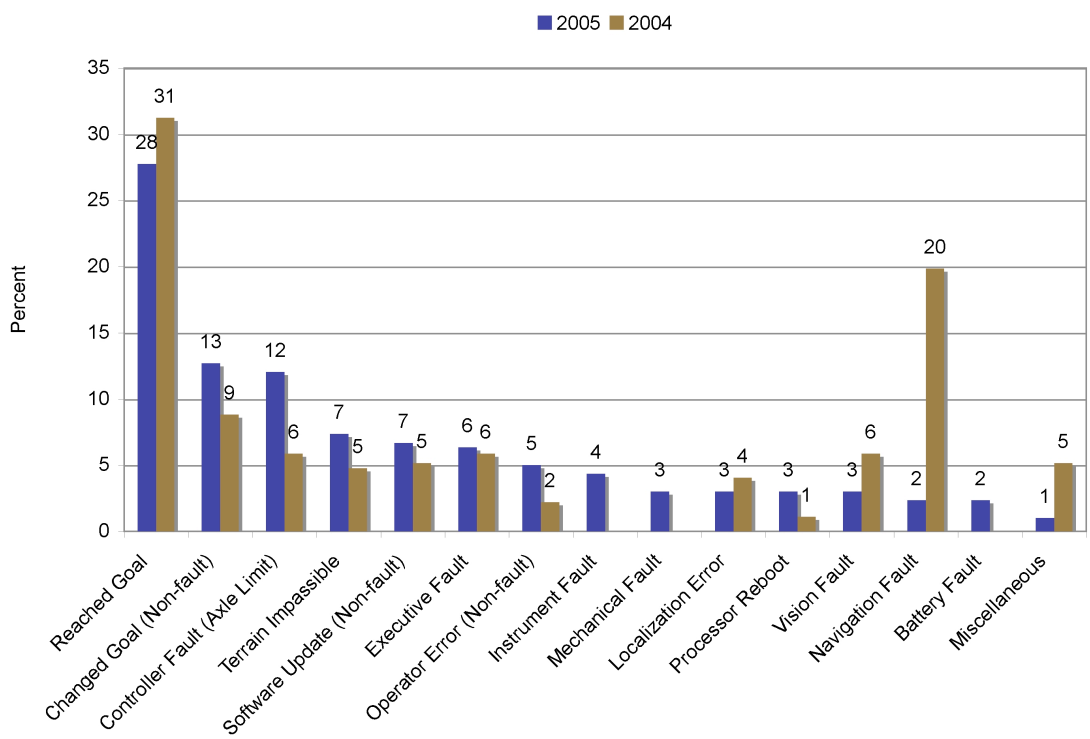

Figure 6. Autonomous traverse termination conditions

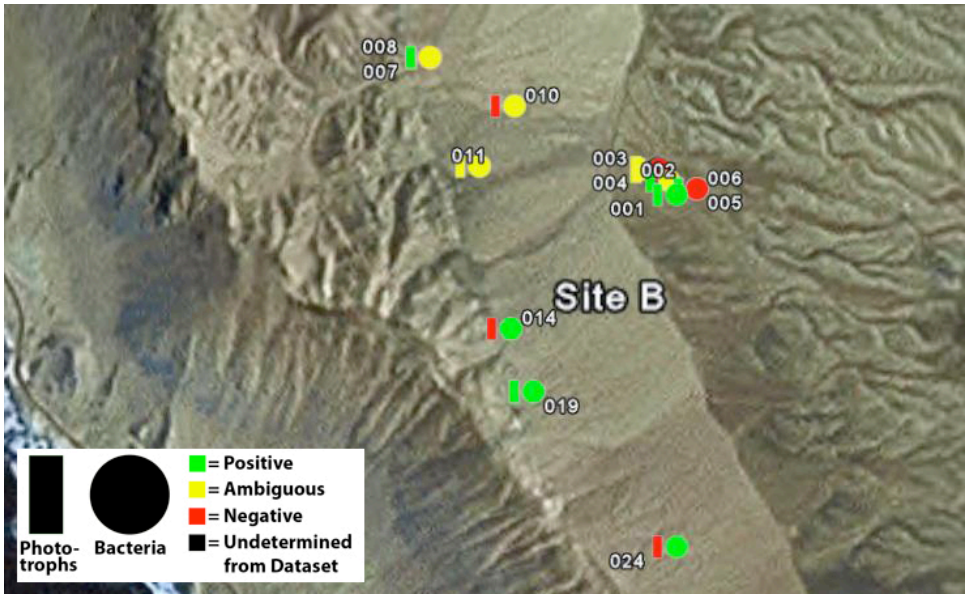

Figure 7. Biogeologic mapping at field site B. Measurements of the presence and two classes of microorganism are indicated at the location where the rover observed them.

survey in desert terrain. These results provide insight into the design of an effective robotic astrobiologist for future planetary investigations and into methods of conducting automated field survey and mapping. The long-distance navigation concepts demonstrated here are now incorporated into the Mars technology program to support future long-range rovers.

Our research continues in over-the-horizon navigation, particularly the use of far-field terrain evaluation, and rover autonomy with growing emphasis on science. Science autonomy enables a rover to reason about scientific objectives and make better decisions about instrument application and data validity and selection. [7,12] There may be significant benefit to future planetary explorers.

6. Acknowledgments

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