on a 6m diameter curved screen spanning 200° horizontally and 60° vertically. From an audience of about 30 viewers, a driver is selected to direct the robot's path and the pan and tilt of the panospheric imagery. Other audience members choose what technical information is overlaid on the display. In addition, imagery and robot status are available in real time on the Internet.

The Science Center also features kiosks that describe the Trek, various technologies utilized by the robot, the science performed during the Trek, and information about the Atacama Desert and Chile.

13 Operations and Experiments

Although the primary objective is to traverse 200km under transcontinental control, the Atacama Desert Trek pursues complementary operational, technical, scientific and outreach goals. These are profiled in Table 2.

Item	*Comments*
Operations	
Remote Operations	Operations from Carnegie Science Center Operations from NASA Ames
Time Delayed Teleoperation	Operations with additional delay to simulate Moon and Mars missions
Reduced Control Modes	Operations without panospheric camera Operations at low bandwidth comm Operations without laser Operations without stereo
Round the Clock Operations	Limited night operations
Technology	
Locomotion	Terrain negotiation, success rate, power, torque and drawbar pull measurements to validate locomotion configuration.
Panospheric Camera	Compare teleoperation using panospheric camera and conventional camera
Antenna Pointing	Continuously evaluate data throughput and pointing quality
Safeguarded Teleoperation/ Autonomous Driving	Compare modes with direct teleoperation.
Position Estimation using Skyline	Compare position estimation using skyline views vs. conventional sensors
Science	
Meteorite Search	Perform patterned search to look for meteorites; Detect meteorites using metal detector
Geological Survey	Remote geological survey performed by team of geologists at NASA Ames. Three simulation modes: Lunar, Mars and Antarctic simulation.
Stateside	
Novice Drivers	Novice drivers and scientists drive Nomad from CSC/NASA Ames.
Immersive Visualization	Panospheric images displayed in Electric Horizon theatre.
Driving Experience	Visitors to CSC experience rover motion while sitting on motion chairs
Technology Videos	Kiosks at CSC show videos detailing various technologies

Table 2: Operations and Experiments

14 Summary

The purpose of the Atacama Desert Trek is to demonstrate capabilities for high-performance planetary exploration by mobile robots. Breakthrough technologies relevant to locomotion, panospheric and immersive visualization, high data rate communications, position estimation, safeguarded teleoperation and autonomous driving, and remote geology are demonstrated. Beyond technical objectives, the Atacama Desert Trek sets a new standard for operational and public outreach for robotic exploration experience.

Acknowledgments

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[9] Web: http://img.arc.nasa.gov/marsokhod/marsokhod.html

[10]Web: http://www.ri.cmu.edu/atacama-trek

range data produced by the stereo cameras is reprojected into an overhead map view, and all possible forward paths are evaluated. Potential obstacles are considered for each path, and only when a path is found to be free of obstacles will Nomad be allowed to move in that direction ([6], [8]). This processing occurs in real time, with new maps generated once per second, so the obstacle detection is always one step ahead of the remote operator; as long as the stereo range data is good, Nomad can immediately determine if it is safe to proceed in a given direction.

Nomad's sensors also enable it to drive autonomously, without requiring intervention by a remote operator. Robot autonomy is a critical technology for planetary exploration, since it enables faster progress in difficult or isolated areas over greater distances, and reduces operator fatigue. In the Desert Trek, remote operators can specify a direction of travel and watch as the internal safeguarding system drives Nomad safely toward that goal.

9 Internal Safeguarding

Nomad's successful operation depends on locomotion, power, thermal, communications, visualization and computing systems functioning in harmony. Nomad is designed to maintain this internal harmony, thus minimizing the number of operators required as well as the fatigue inherent to teleoperation.

Nomad monitors the health of each component and modifies overall operating conditions if isolated variations occur. For example, if the Comm link decreases from 1.5Mbps to 0.15Mbps, the cameras automatically scale back output to the most useful views, and locomotion electronics limit speed to 0.2m/s to accommodate the operator's limited visual scope. A sample set of internal safeguarding tasks include: limiting rover speed and turning based on extremity of slope, thermal protection, and comm scheduling.

10 User Interface

Nomad's panospheric camera and ability to return a high bandwidth data stream sets the stage for a user interface with rich, active imagery. A novel method of compressing, transmitting and rendering images allows an observer to smoothly and seamlessly look around the robot's environment. New images are merged at a rate that just saturates the available communication bandwidth. This visual display produces a sense of presence at the robot's location for scientists, operators, and the public.

In addition to visual imagery a virtual dashboard (Figure 9) provides consistent appearance and interaction, functional organization, an uncluttered layout, simple command generation, and visual indication of safeguards.

With Nomad's virtual dashboard, the operator can command individual components, drive the robot, or set

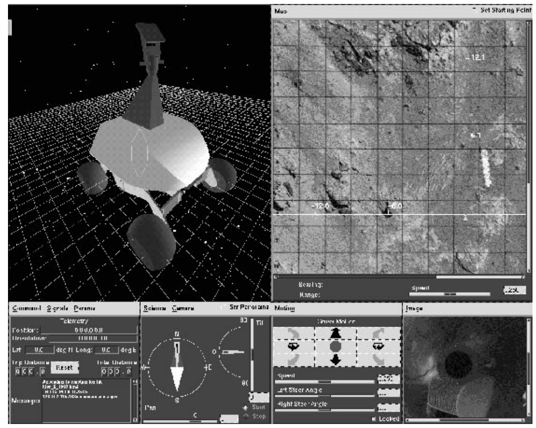

Figure 9: User Interface

a direction for the autonomous navigation system. A compass clearly indicates current direction, while a thermometer gives continuous readings of temperatures.

The virtual environment display (shown in the upper left of Figure 9) provides a perspective view of the robot. All robot motions are rendered in real time. With the freedom to "fly around" and view the robot as it moves, operators have increased situational awareness and driving efficiency.

11 Science

Nomad incorporates instruments for remote geological studies of the Atacama Desert. Scientists are performing three mission simulations that are analogs to remote operations on the Moon, Mars and Antarctic. These are:

<u>Lunar test</u>: Perform "geology-on-the-fly" in which scientists attempt to assess trafficability and gross geology while keeping the rover in motion 75% of the time.

<u>Mars test:</u> Reduce the communications bandwidth and try to correctly characterize the climate, geology and evidence of past life at the site.

<u>Antarctic test:</u> Perform pattern searches for specific rock types and evaluate methods for identifying meteorites in Antarctica.

The objectives are: to develop and evaluate exploration strategies, to devise methods of cooperation among distributed science teams, to create and refine telepresence control environments and to evaluate remote sensing technologies. Experience to date is that scientists are less efficient and less accurate (in correctly characterizing a site) when they operate remotely [9]. The intent of these simulations is to identify methods and technologies that improve the process.

12 Stateside and Public Participation

During operations in South America, Nomad is controlled from two sites in North America: the Carnegie Science Center and NASA Ames. The Science Center's Electric Horizon theatre displays panospheric imagery antenna and pointing device for orienting the antenna. The low bandwidth radio carries all the status/command/control information. The repeater station communicates with the operations (Ops) truck using another wireless bridge/radio. From a 1.8m Ku-band dish on the Ops truck, the information is transmitted to a satellite, where it is cross-strapped to a C-Band transponder and transmitted back to the U.S. This information is downlinked at a receiver station in Pittsburgh where it is then sent to the science center via land lines.

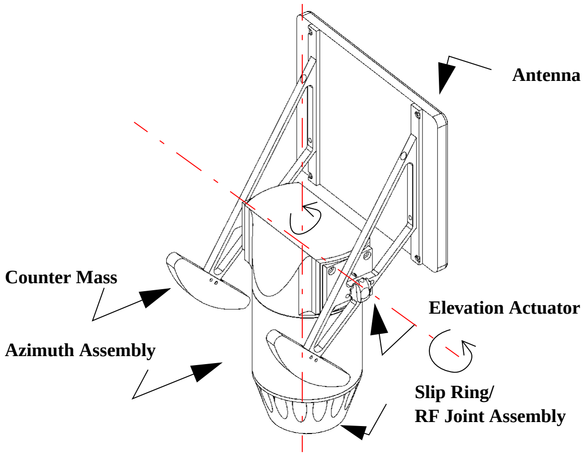

Figure 6: Antenna Pointing Mechanism

In a custom design, the antenna pointing device is a balanced mechanism (Figure 6) that can steer the antenna at high slew rates up to 60°/s to compensate for vehicle motion. The pointing mechanism orients the onboard antenna towards a stationary receiver antenna at a relay station located 0-10km away. The antenna pointing technology uses an IMU, Differential GPS (DGPS), compass, inclinometers and encoder data to generate the necessary position estimates for accurate pointing control.

7 Position Estimation

Estimation of robot position and orientation is accomplished by fusing data from a range of sources. DGPS satellite data is the primary source for position estimation, with local updates provided by velocity data from the wheel encoders (odometry). The DGPS resolution is on the order of 20cm, given sufficient satellite coverage. The rover orientation data is provided by combining data from a gyrocompass/inclinometer suite with integrated rotation rate data from an IMU. The compass/inclinometer suite provides magnetic north heading as well as roll and pitch information to a resolution of 0.1°. The IMU provides rotation rate values about its three orthogonal axes. Best estimates within each domain (linear position and rotational orientation) are accomplished by merging the data from the relevant sensors. This data is weighted according to appropriate reliability metrics, such as rms positional error and satellite coverage (for the GPS), and measured rms signal error (for the IMU).

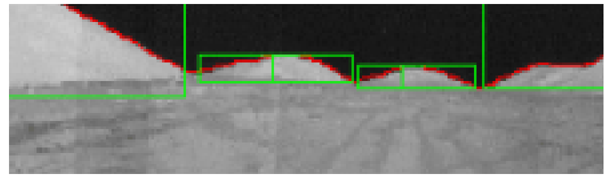

Figure 7: Skyline Views Based Position Estimation

Nomad also uses skyline views to estimate position [3]. This is relevant to mobile robot operations on planets, which involve analyzing images sent by the robot and overlaying information about the robot's environment onto the images. Algorithms for pose estimation from outdoor imagery allow users to automatically detect the position of the robot and determine the relationship between terrain information and image pixels.

8 Safeguarded Teleoperation

The vast distance and inherent communication delays encountered in planetary exploration present a fundamental technical barrier to direct teleoperation of planetary robots. If a human operator is responsible for robot safety, the robot must pause for the duration of the delay in image transmission between each move. Nomad mitigates this limitation by autonomously distinguishing between safe and dangerous routes, using onboard sensors and computing. Any nearby obstacles are discovered and mapped using stereo cameras and a laser scanner, and registered using onboard position estimation. This knowledge of its environment enables two unique driving modes: *safeguarded teleoperation* and *autonomy.*

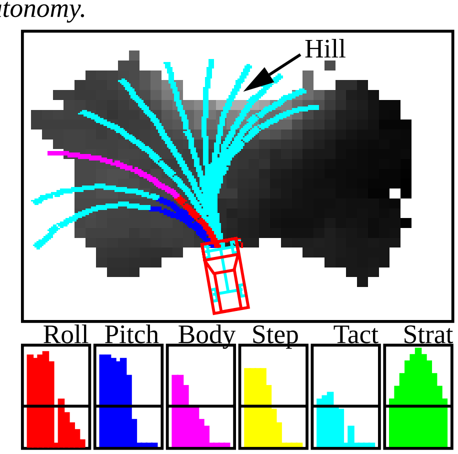

Figure 8: Onboard Obstacle Detection

Safeguarded teleoperation gives the remote operator direct steering control over the robot, as long as the commanded direction is deemed safe by the onboard sensors. If the human operator should direct Nomad onto a dangerous path, the safeguarding system will override that command and either force Nomad to stop or to steer around the obstacle. Figure 8 illustrates the information considered by the onboard safeguarding system; the

Item	*Value/Comments*
Physical	
Mass	550kg
Power Consumption	2400W max.
Size	1.8m x 1.8m x 2.4m Stowed 2.4m x 2.4m x 2.4m Deployed
Locomotion	
Wheel Size	76.2cm Diameter x 50.8cm Width
Static Stability	$\pm 35°$
Obstacle	0.5m height (atleast)
Speed	0.5m/s Maximum 0.3m/s Average
Imaging	
Panospheric Camera	1k x 1k color at 6Hz
Rear Camera	1k x 1k grayscale, occasional
Compression	100:1; DSP based wavelet compression
Communication	
Data Rate	1.54Mbps (Total)
Equipment	Wireless ethernet bridge using high gain antenna for images and low bandwidth radio for status/command/control
Sensors	
Position Estimation Sensors	IMU, GPS, gyrocompass, wheel encoders, skyline positioning from imagery
Navigation Sensors	Stereo cameras, laser scanner
Science	
Weather Sensor	Temperature, wind velocity, humidity
High-Res Camera	3 CCD color camera with a pan/tilt mechanism for remote geology
Metal Detector	Meteorite search
Computing	
Real Time Computer	50MHz 68040 & 40MHz 68030 running VxWorks
Imaging Computer	200MHz Dual Pentium Pro running NT
Navigation Computer	133MHz Pentium running Linux
Operation Modes	
Safeguarded Teleoperation	Remote driver, onboard safety enabled
Autonomous	No human intervention
Direct Teleoperation	Remote driver, onboard safety disabled

Table 1: Nomad Specifications

5 Visualization System

Traditional cameras provide limited resolution and field of view for teleoperating robots to their remote human controllers. Nomad's panospheric camera conveys spherical images of a complete horizon to provide operators and observers improved coverage and wider imagery for driving through and viewing planetary terrain [7].

Nomad uses a panospheric camera (Figure 4) as its primary camera. Mounted in the "driver's seat" area on the rover, the camera provides views to the front and left side of the robot, and horizon views to the right and back, generating a full panorama from 90° below to 30° above the horizontal. Acquired at 6-8Hz, panospheric images are compressed using DSPs and sent to the control sites where they are decompressed. The decompressed images

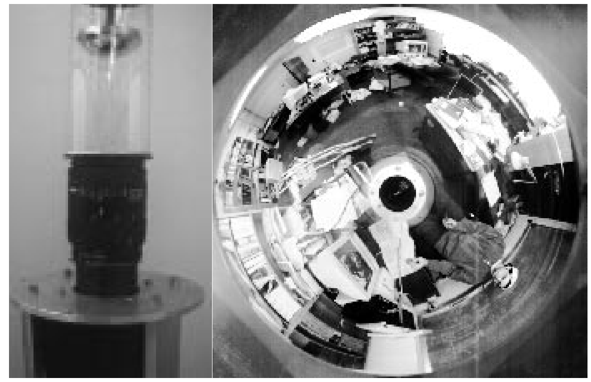

Figure 4: Panospheric Camera & an Image

are then sent to the appropriate display (e.g. monitor or hemispherical dome display).

An additional camera (see Table 1) located at the back of the robot captures views that the panospheric camera cannot provide due to its placement. Because there are no stereo or laser sensors in the back of the robot, this camera also enables an operator to assess what is behind the rover in situations where the rover needs to drive in reverse.

6 High Bandwidth Communication

Field robots commonly use omnidirectional antennas for communication with remote control stations. This scheme restricts the bandwidth (nominally < 100kbps) and range (nominally < 1km) due to the limited power available onboard the robot [2]. However, Nomad uses an actively pointed high gain antenna to achieve high data rate communication over extended range.

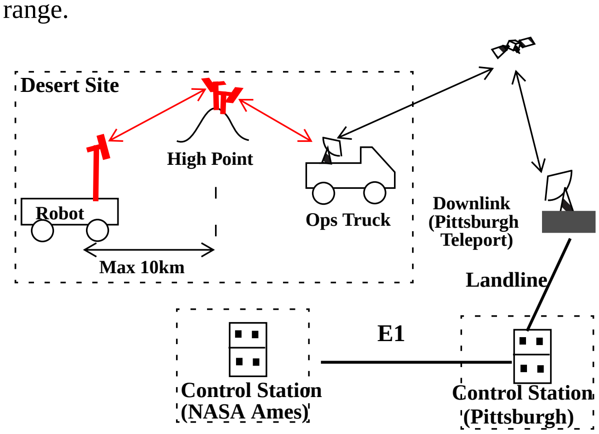

Figure 5: Communication Overview

Figure 5 presents an overview of the communication path employed in the Atacama Desert Trek. The robot talks to a repeater station located at high elevation, which in turn relays to a satellite ground terminal. The information is communicated via satellite to a receiver station in Pittsburgh and then forwarded to the control stations using land lines.

Nomad carries a wireless bridge and a radio. The wireless bridge provides the high data rate required to transmit imagery from the panospheric camera; however, this configuration necessitates Nomad's high gain an Inertial Measurement Unit (IMU), and the Global Positioning System (GPS). The Desert Trek also demonstrates new visual position estimation technology, using panoramic skyline images to determine position on an existing terrain map.

- Safeguarded Teleoperation. Traditional robotic teleoperation requires a human operator to identify and avoid obstacles, as well as a continuous communications link. Nomad's onboard navigation sensors and computing allow it to reason about obstacles and navigate in reduced communications areas without operator assistance. This experiment determines the potential of such capabilities to aid planetary exploration.

- Remote Science. Nomad uses patterned navigation with position registration and onboard sensors to search for interesting rocks and meteorites and to generate geological maps.

The Desert Trek involves public participation through control operations at the Carnegie Science Center (CSC) in Pittsburgh, PA and NASA Ames in Mountain View, CA. Nomad's safeguarded teleoperation, combined with a rich, interactive user interface, allows novice operators the opportunity to operate Nomad safely from remote control centers. The images and data from Nomad are also available on the Internet in real time.

2 Site Description

Located in northern Chile, the Atacama Desert (Figure 2) offers terrain suitable for demonstration of robotic capabilities in planetary exploration. This desert landscape includes craters, rocks, and loose sand, with vegetation completely absent due to the lack of precipitation and high mineral content of the soil. The selected site features varied topography suitable for antenna placement, views of the surrounding landscape, and operational access. The terrain is challenging and includes obstacles deemed impassable by Nomad. The

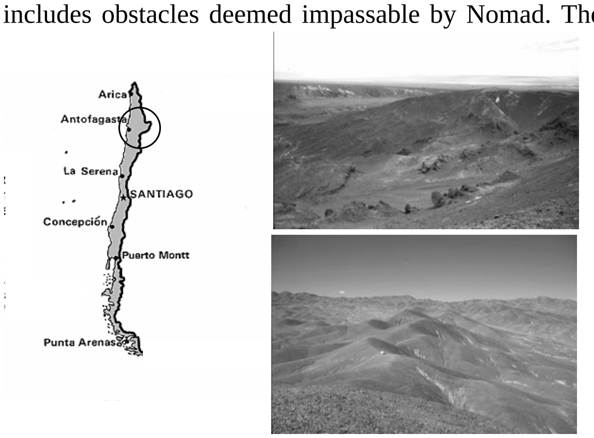

Figure 2: Site Selection

Atacama's location within the same time zone as one of the two control centers (CSC) also simplifies coordination of operations.

3 Nomad

Nomad is responsive to parameters of planetary locomotion, navigation, remote imagery and communications. Weighing 550kg, Nomad features four wheel drive/four wheel steering, with a unique transforming chassis (Figure 3) that expands to improve stability and propulsion over variable terrain.

Nomad is self-sufficient, with onboard sensing, planning, and navigation for safeguarded and autonomous driving. Panospheric as well as conventional cameras provide imagery, and an innovative pointing mechanism facilitates high bandwidth communication from Nomad. VEVI, a user interface developed by NASA Ames, provides a rich interactive experience for remote drivers and observers [4].

Table 1 presents specifications for Nomad. The following sections describe the primary onboard technologies, as well as the user interface, science and control scenarios.

4 Locomotion

For terrestrial and planetary exploration, robotic locomotion must have traction, steering, and suspension responsive to terrain marked by craters, rocks, and loose sands and soils. Nomad's four wheel drive/four wheel steer locomotion and innovative transforming chassis provide the appropriate balance of capabilities and complexity for effective traction and mobility in soft soils, sands, and slopes [1].

Nomad achieves traction in soft soils and on slopes using four aluminum wheels with cleats along the circumference. In-wheel propulsion, independent of steering and suspension, provides simplicity and thus reliability.

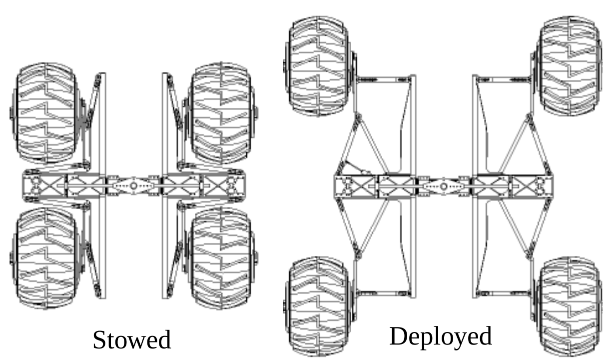

Figure 3: Transforming Chassis

Nomad's chassis expands, compacts, and steers by driving two pairs of four-bar mechanisms, one on either side of the robot. This capability not only allows Nomad to adapt its footprint to the terrain but also enables steering by differential actuation of the two deployment motors. The "deployed" mode improves Nomad's stability and propulsion over variable terrain, facilitates body posture averaging for smooth driving motion, and ensures consistent, reliable operation of sensitive onboard sensors and processors.

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Atacama Desert Trek: A Planetary Analog Field Experiment

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Abstract

Nomad, a planetary-relevant mobile robot, is chartered to traverse 200 kilometers across the Atacama Desert in Chile, exploring a landscape analogous to the surfaces of the Moon and Mars. Operating both autonomously and under the control of operators thousands of kilometers away, Nomad and the Desert Trek address issues of robotic configuration, communications, position estimation and navigation in rugged, natural terrain. The field experiment also serves as a testing ground for remote geological investigation, paving the way for new exploration strategies on Earth and beyond. Finally, by combining safeguarded teleoperation with onboard panoramic visualization and a novel user interface, the Atacama Desert Trek provides the general public an unforgettable interactive experience and its first opportunity to remotely drive an exploratory robot.

An unprecedented demonstration, the Atacama Desert Trek sets a new benchmark in high performance robotics operations relevant to terrestrial and planetary exploration.

1 Overview

The primary objective of the Atacama Desert Trek is to develop, evaluate and demonstrate a robot capable of long distance/long duration planetary exploration [10]. During the Atacama Desert Trek, the robot **Nomad** (Figure 1) navigates 200km of the planetary-like Atacama Desert in South America while under the control of operators in North America.

The field experiment addresses issues in the following areas of remote planetary exploration:

- Locomotion. The robot's locomotion provides mobility and terrainability appropriate for the mission environment. Nomad demonstrates and verifies the viability of four wheel drive/four wheel steer locomotion, as well as an innovative transforming chassis for planetary exploration.

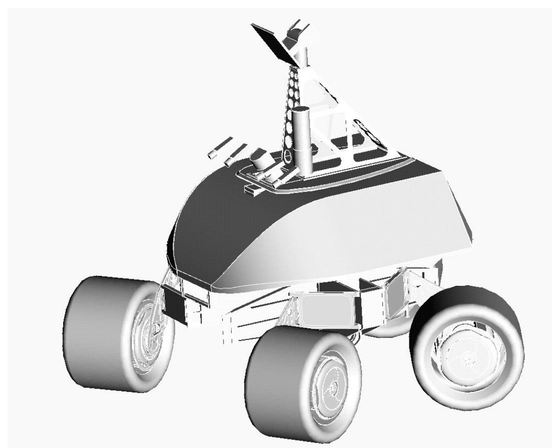

Figure 1: Nomad (2.4m x 2.4m x 2.4m)

- Imaging. Traditional cameras provide limited resolution and field of view for teleoperating robots. Nomad carries an innovative panospheric camera that generates rich broadcast quality imagery with an ultrawide field of view. The experiment attempts to prove the advantages of this camera for teleoperation and for imparting remote experience from a mobile robot.

- Communication. Mobile robots normally use an omnidirectional antenna for communications and are limited in data rate and range of communication. Nomad achieves high data rate communication over extended range using active pointing of high gain antennas. The experiment addresses issues in pointing from mobile robots, demonstrates the feasibility of this scenario, and evaluates its effectiveness.

- Position Estimation. Nomad ascertains its position using traditional sensor-based methodologies incorporating odometry, inclinometers, a gyrocompass,