Robotic Search for Antarctic Meteorites Demonstration

Technical and Administrative Contact:
Name
emailname@cmu.edu
412-2 8-xxx (Fax: 412-2 8-xxx)

The Robotics Institute
arnegie Mellon Universit
5000 Forbes Avenue
Pittsburgh PA 15213

For the period Oct 1, 1999 through September, 2000

Amount requested: $1,000,000

Red Whittaker, Senior Research Scientist, Computer Science Dept. & The Robotics Institute	Date
Dimi Apostolopoulos, Systems Scientist The Robotics Institute	Date
Takeo Kanade, Director The Robotics Institute	Date
Jim Morris, Dean School of Computer Science	Date
Susan Burkett, Associate Provost Carnegie Mellon University	Date

1. Objectives:

The primary goal of this task is to enable autonomous discovery of Antarctic meteorites using robotic search and automatic classification. The theme of the task provides an ideal format for demonstration of robotics in an environment and operational scenario analogous to exploration of the lunar and Martian poles. The proposed effort will support planetary science through the discovery of new meteorite samples, which provide the only significant source of geological material from outer space. Moreover it will augment the human search for Antarctic meteorites through thorough area searches and in-situ sample classification.

Using a winterized Nomad robot this task has demonstrated the feasibility of automatic rock and meteorite classification from multiple sensors and autonomous navigation in polar terrains. The primary technical objectives for FY00 are integration of all autonomous capabilities into Science Autonomy—an architecture for intelligent exploration, automatic classification of samples, and coordination of mobility and manipulation for precise instrument placement—and demonstration of an autonomous search for new meteorites in Antarctica.

2. Justification & Impact:

Demonstration of fundamental technologies significant to NASA's planetary exploration program and confirmation for the feasibility of system-level concepts in terrestrial planetary analog environments are the goals that justify the proposed work. The robotic search for Antarctic meteorites offers an ideal test case for demonstration of the capabilities of planetary rovers with emphasis on *autonomous geological exploration and in-situ sample classification*, themes of great importance to the Space Science Enterprise [1]. Development and evaluation of mobile robots capable of extended search for meteorites in Antarctica will further NASA's search for planetary life. The technical objectives of scientific exploration, environmental survival, and self-sustained mission performance are fundamental to NASA's charter in exploration and are directly relevant to the joint NASA/NSF initiative to operate in the Antarctica as a planetary analog.

This task's developments and demonstrations have had and will continue to have a significant impact on NASA's research and the perception of NASA as a whole. Other NASA programs such as Intelligent Robotics have adopted technologies introduced by this work [2]. Our program trains engineers, scientists and new doctoral students, and involves undergraduates in critical project areas. Through teaching, outreach, dissemination of knowledge and broad student participation through initiatives such as the Big Signal Project, we promote NASA's commitment to education [3]. Through impressive field demonstrations, we hope to capture and hold public attention and to encourage new thinking about the roles of robotics and of NASA.

3. Approach

This task combines advanced research with engineering to achieve programmatic goals, innovation, and quantifiable advances over the state-of-the-art. Our approach has been to investigate *robotic sample classification* and *autonomous exploration of an Antarctic region*—the two main aspects of robotic search for Antarctic meteorites—concurrently yet in parallel tracks to ensure thorough research of issues involved in each aspect. Through incremental development, persistent field testing and two Antarctic demonstrations of escalated technical agenda, we have achieved independent validation of science and exploration capabilities. In 1998 this task logged more than 500 hours of field work and accomplished classification of more than 50 rocks and meteorites, 10 km of autonomous navigation, and 200 hours of robotic experiments in a six-week expedition to Patriot Hills, western Antarctica.

The first priority for this task is on research in meteorite sensing modalities and machine learning techniques for automatic classification of samples. Our work to date has concluded that combined visual imagery and reflection spectroscopy are adequate for automatic discrimination of meteorites from terrestrial rocks. To improve the effectiveness of robotic searches, a hierarchical approach to data collection has been devised in which, low-deployment-cost/low- information-gain sensors are first to be used followed by high information-gain sensors that require precise deployment to a sample [4]. Intelligent sensor selection and improvements on the robustness of automatic classification will be the key efforts in FY00.

The second priority is on the development of robust autonomy for polar exploration. Adaptation of technology developed by the Lunar Rover and Atacama Desert Trek tasks has facilitated the demonstration of safeguarded searches including obstacle avoidance in ice-covered terrains [5]. To make a search a feasible robotic challenge, ice stranding surfaces—usually not exceeding a few square kilometers in area—should be searched first because they tend to have a much higher density of meteorites [6]. The fact that large meteorite numbers can be found in small stranding surfaces, has motivated the development of patterned search techniques for optimal area coverage under time and power constraints. Research on the merits of combined coverage search and robotic geological profiling of a region based on autonomous scientific observations and classification of samples will take place in FY00.

To enable a seamless execution of autonomous exploration and robotic sample classification, we have researched and developed a hierarchical distributed control architecture, called Science Autonomy. This novel architecture integrates mission planning, safeguarded obstacle avoidance, science sensor management and automatic sample classification under a framework of fully networked processes.

In relation to technology validation, our approach has been to build on the existing capabilities of the Nomad robot and to field test new components and technologies in an incremental fashion. In January 1998, a scouting expedition to Antarctica field-validated individual robotic components and meteorite-detection sensors for the purpose of quantifying their performance before their incorporation into Nomad. During a second Antarctic expedition in late 1998, Nomad sought out and classified meteorites at Patriot Hills.The primary demonstration evaluated the robot’s classifier in distinguishing between and characterizing rocks and meteorites using high-resolution imagery and optical reflection spectroscopy. Nomad correctly classified 10 of 15 planted meteorites and 38 of 42 native rocks.

A second independent demonstration conducted a field evaluation of robotic capabilities including autonomous navigation of ice and snow using stereo vision and laser perception and area patterned coverage planning. Because the vast majority of terrain negotiated was featureless, stereo matching from disparity maps was impractical. Lack of contrast due to excessive light diffusion during overcast days further hampered stereo. Laser range finding was effective in all cases with the exception of situations in which beam interference from drifting snow led to incorrect range measurements. Despite the absence of stereo data, Nomad achieved 10.3 km of autonomous navigation using laser as the only terrain-perception sensor. A comprehensive discussion about the technology and demonstration results from the 1998 robotic expedition to Patriot Hills can be found at [7] and [8].

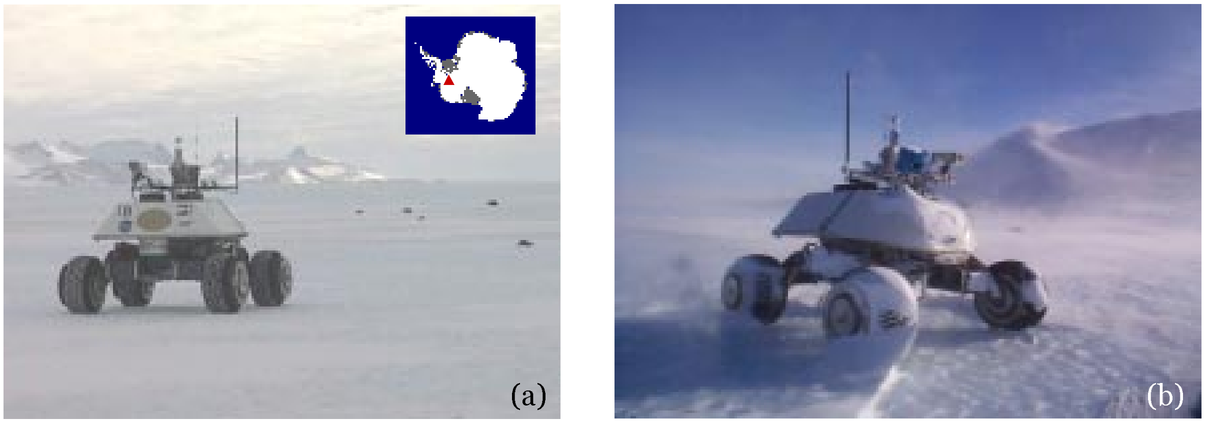

FIGURE 1: Nomad in an autonomous navigation demonstration at Patriot Hills, November 1998 (a). During the six week expedition, the robot endured wind chills as low as -70°C and wind gusts up to 75 km/h (b).

3.1 FY00 Effort

In FY00 we will augment the functionality and robustness of Science Autonomy and demonstrate combined autonomous search and in-situ classification of samples through:

- **Integrated planning and navigation in polar terrain:** This technology not only requires development of a navigational sensing scheme that is robust in polar conditions but also of high-level planning software to coordinate Nomad's existing obstacle avoidance capability with a planner that executes patterned search optimized for critical performance metrics, such as total percent of search area covered or minimization of power consumption.
- **Automatic acquisition of science targets:** Using images the robot must autonomously identify targets and segment them from a background of ice and snow under various lighting and weather conditions, from bright sunlight to blowing snow. The target acquisition must be robust enough to reject false negatives such as shadows casted by rocks.
- **Autonomous precise placement of science sensors:** Identification of meteorites requires multiple sensing modalities, some of which demand very accurate placement of sensors. In addition to capturing high-resolution imagery of a potential meteorite, a visible-light spectrometer and metal detector must be placed very near the object being examined, which requires use of a manipulator arm. Control of this arm is a critical issue and must involve the use of visual servoing for precise placement of science instruments. At this time, the manipulator arm and visual servoing software are undergoing performance tests.
- **Robust classification of new samples:** This component involves the ability to correctly differentiate terrestrial rock samples from meteorites using the sensor data gathered. The scheme used must be accurate so that the robot does not overlook any meteorites or generate too many false positives.

The integration of these technologies into Science Autonomy should take into account the unique aspects of the Antarctic environment and good software engineering principles. A practical understanding of lighting conditions, shadowing, terrain variations, and rock distribution in the targeted search environment will allow the fine-tuning of software parameters and mechanical designs that will maximize reliability and efficiency. The architecture will be modularized and communication will generally be performed through well-defined client/server interfaces that abstract implementation details of each module. The design and combined functionality of Science Autonomy are summarized in the following paragraphs.

Science Autonomy (SA) enables Nomad to execute a command to search a specified area, to avoid any obstacles encountered and to perform an in-situ classification of potential meteorites found. The structure of SA can be described as a three-level hierarchy (Figure 2). The lowest level is that of the *physical sensor*. These sensors allow the science autonomy system to observe the world. SA has two operational modes: acquisition and identification. In acquisition mode, science autonomy attempts to find new targets in the area around the robot. In identification mode, study and classification of a target takes place. To carry out both objectives, the physical sensors may have to function in very different ways or have to coordinate with other sensors. Therefore the *action coordination* level of the system organizes various physical sensors in different ways to accomplish the goals of *planning*. The planning level examines the results generated by the action-coordination level and creates a plan that will optimize mission variables such as power and time limitations.

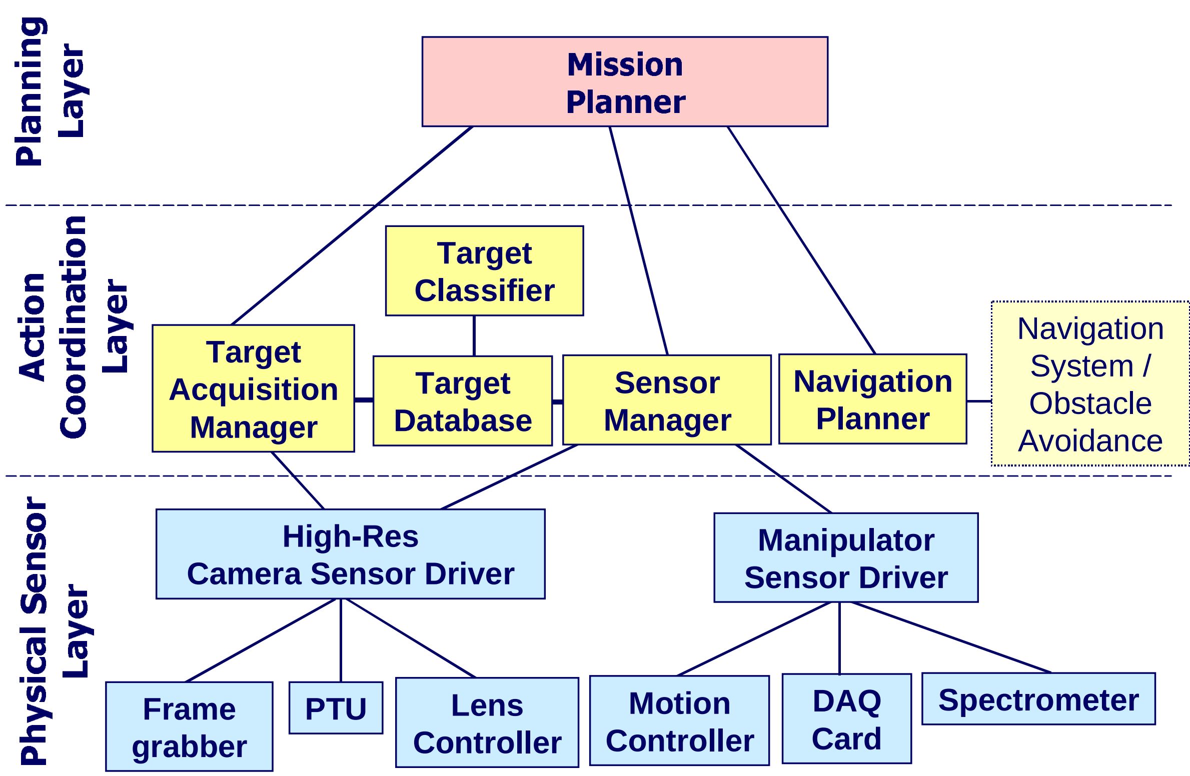

FIGURE 2: Science Autonomy architecture.

The *mission planner* coordinates all activities. It selects an optimal area coverage pattern to exhaustively search an ice field. Throughout the search, Nomad's autonomous navigation system operated by the *navigation manager* serves two purposes. First, it keeps the robot away from obstacles. It does this by integrating terrain data from stereo cameras and a laser rangefinder as well as by monitoring inertial sensors for dangerous roll or pitch values. Second it implements waypoint navigation, which enables the robot to maneuver within a particular tolerance to a set of specified goal locations. aypoint navigation receives a set of differential Global Position System (DGPS) coordinates and directs Nomad in straight lines between the coordinates. The module attempts to bring the robot within an error radius of each way point. Because polar weather such as blowing snow can limit the effectiveness of terrain sensors, an error recovery module monitors the status of the robot for problems not noticed by the terrain sensors. In its current form, it detects two kinds of problems; when possible steering arcs are impassible because of obstacles and when the roll or pitch of the vehicle has exceeded nominal values. If a problem is detected, error recovery will suspend waypoint navigation. It will also initiate a back-up maneuver along the robot's previous route.

During area coverage pattern execution, a *target acquisition manager* monitors data from a set of acquisition sensors capable of finding new meteorite targets on an ice field. A high resolution three-chip color CCD camera mounted on a pan/tilt unit serves as an acquisition sensor. Approximately every second, pixels in an image are classified into rock or ice categories. hen one or more groups of pixels appear as possible meteorites, the target-acquisition manager estimates the targets' DGPS coordinates based on the assumption that the ground is a perfectly flat plane. All of this information is entered into a central *science database*.

The mission planner places new targets into a priority queue sorted by distance from the robot. Considering one target at a time, the mission planner requests sensor deployment costs and the cost of maneuvering the robot as it advances toward the target within the work space of the sensors. These costs are weighed against the benefits of continuing a search pattern and an estimate of the information that could be gained by the acquisition of additional sensor data. This estimate is a measure the classifier's confidence in its ability to identify a target from prior sensor data. The mission planner can then decide to continue following the pattern or to investigate the potential meteorite. After a decision to investigate, the mission planner then selects a sensor with the highest information-gain-to-deployment-cost ratio. If necessary the robot may move within the sensor's field of operation, which contains the target.

The *sensor manager* coordinates deployment of the sensor to the target's estimated DGPS location. This eliminates the requirement that the acquisition sensor track the target during deployment. The location estimate may contain errors due to deviations of the ground from a flat plane, and sensor deployment must be robust enough to correct for these errors. After any necessary calibration, sensor data acquisition takes place. The new data are placed in the database, and the classifier processes them to update its classifications and estimated information gains. Finally the mission planner closes the science autonomy control loop by analyzing the new estimated information gains and deployment costs for other sensors at Nomad's disposal. If the classifier is very confident in its results, further sensor data will most likely only verify the current classification. The mission planner will therefore decide to end its investigation of the current target. Otherwise additional sensors are used.

The *target classifier* lies is the key to Nomad's autonomous capability for classification of meteorites and native rocks. The Bayes network-based classifier uses the visible spectrum (400—1,000 nm) for identification of rocks. The classifier detects peaks and troughs in spectral signature by computing the normalized correlation coefficient of the spectrum with a fixed set of Gaussian templates, each with a predetermined width and central wavelength. A positive coefficient indicates a reflection peak, whereas a negative value indicates a trough. Spectrally flat areas have zero correlation. The classifier also computes normalized red, green and intensity coefficients. The intensity coefficient is fairly unreliable but still has considerable diagnostic value. A Bayes network, encoding the statistical distribution of spectral features (correlation coefficients and red, green and intensity values) for each rock type along with their assumed prior probabilities, computes a confidence value from the spectra for each rock type in the network. The network confidence for each rock type corresponds to the posterior probability of the rock being examined, given the current spectral data. Because the classifier output provides evidence of a rock being a meteorite and does not produce a binary classification, it is difficult to make precise inferences on the success rate of the field measurements. A simplistic measurement can be obtained through classification of rock as either a meteorite or a terrestrial rock depending on whether the classifier determines it to be more or less likely to be of extraterrestrial origin given the spectral data. In field and controlled experiments, Nomad's classifier has succeeded in correctly classifying 65% of meteorite samples and 90% of rocks.

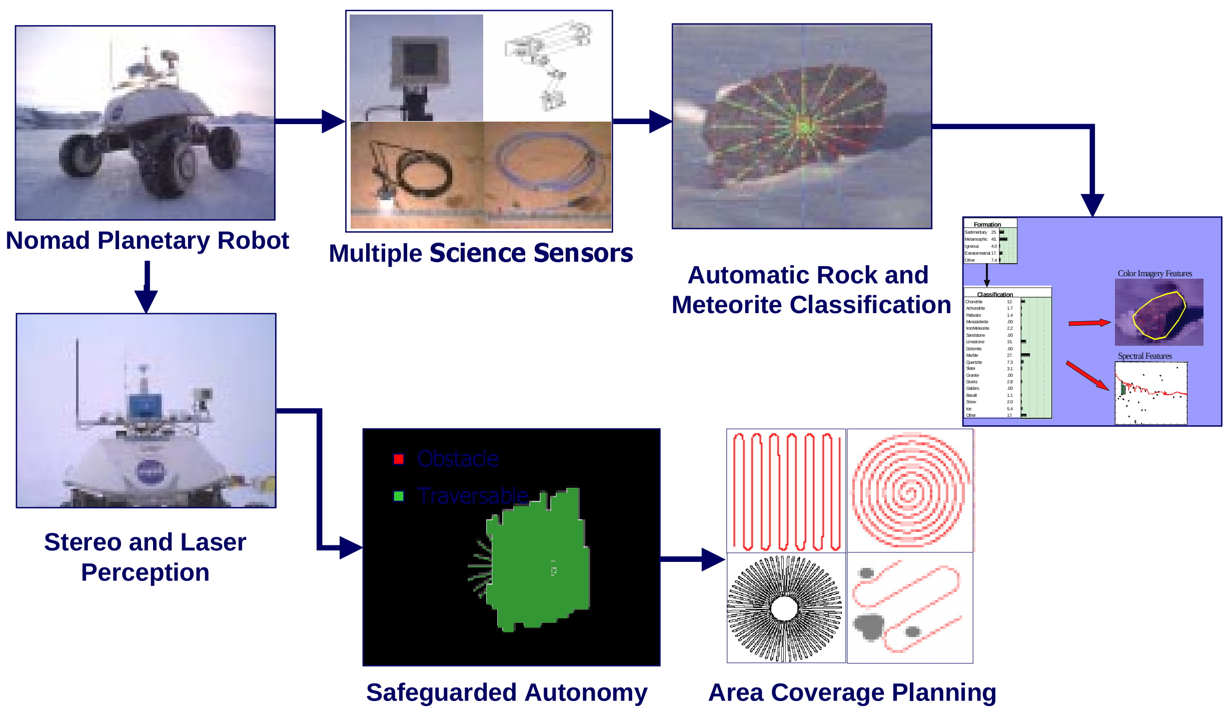

FIGURE 3: Meteorite classification and navigation technologies involving the use of Science Autonomy. The upper track shows the three rock/meteorite sensing modalities (high resolution vision, metal detection, spectroscopy) and manipulator arm design, rock image acquisition, and output from the Bayes classifier. The lower track illustrates Nomad's sensor head, which includes a laser range finder and two stereo pairs, a map developed by its autonomous navigation indicating traversable (green) and non traversable (red) areas and a selection of patterns that the mission planner can issue when Nomad explores an area.

3.2 Antarctic Demonstration 2000

The goals of the 2000 Antarctic demonstration are to discover new meteorites with Nomad and validate Science Autonomy in meteorite searches at Elephant Moraine (76^{o} 17′ S, 157^{o} 15′ E). The proposed demonstration will occur under the auspices of NASA and NS, and in collaboration with the NSF Antarctic Search for Meteorites (ANSMET) field team. Operations will take place in January 2000.

Profile of Meteorite Search Demonstration:

The field demonstration will begin with user control of command Nomad to initiate the search of an area. Nomad's will focus on searching areas of approximately 1 km^2. Once the initial command occurs, the search will commence under the autonomous control of the mission planner. e anticipate that, during a period of four weeks Nomad will explore 2—4 ice fields around Elephant Moraine.

- The mission planner will pick an optimal coverage pattern to exhaustively search the selected area. This coverage pattern will be executed by the transfer of commands from the mission planner to the navigation system. Therefore, during the search, the robot will maneuver itself around potentially dangerous obstacles. The SA will adopt acquisition mode in which the target acquisition manager monitors data from the high-resolution CCD camera mounted on a pan/tilt unit on the sensor mast. Every few seconds, the sensor will present data to the target acquisition manager for analysis. The target acquisition manager will perform thresholding of the image based on pixel color for discovery of dark rocks on the bright ice. hen one or more groups of pixels appear as rock targets, the target acquisition manager will estimate the targets' DGPS locations under a flat- ground assumption. ith this information, new records enter the science database.
- hen the database receives a new record, it will broadcast a message announcing the new information. The mission planner listens for this message. If the mission planner receives one or more new record notifications, it will place them into a priority queue sorted by distance from the robot. Considering the target at the front of the queue, the mission planner requests sensor deployment and robot maneuvering costs from the sensor and navigation manager. These costs are weighed against the benefits of continuing the search pattern. If the mission planner decides to investigate the new target, the SA enters identification mode. Otherwise the task of target acquisition will continue. The SA will then switch to identification mode in which the mission planner chooses the sensor with the best estimated information gain/deployment cost ratio. The mission planner may navigate the robot to an area within the science e manipulator's workspace. If so, the navigation manager will navigate the robot to a target while it avoids any obstacles in its path.
- Once the robot is confirmed to be in front of the target, the mission planner will command the sensor manager to deploy the manipulator arm sensor payload to the target's estimated DGPS location. The sensor manager may calibrate the sensor if necessary and then deploy it to the target. ith the aid of arm, visual servoing techniques will be deployed to overcome errors in the DGPS estimation that may occur because the ground is not flat. After data acquisition, the sensor manager will send the

new sensor information to the database, which will notify the entire SA of new sensor information. Upon receipt of this notification, the classifier will process the new data to update its classification estimates and information gains for the target. The classifier will add these results to the database for future mission planning considerations.

- The mission planner will then analyze the estimated information gain and deployment cost of each sensor. It may decide to redeploy the same sensor again if additional information could be beneficial. The mission planner may also decide to deploy a new sensor. Finally it may choose to cease investigating the current target and to either move to the next target or to continue the pattern.

Nomad will repeat this sequence hundreds of times during the expedition. Elephant Moraine is known to contain meteorite samples mixed with a large number of terrestrial rocks; a fact that makes the robotic discovery and classification of new meteorite samples a great challenge.

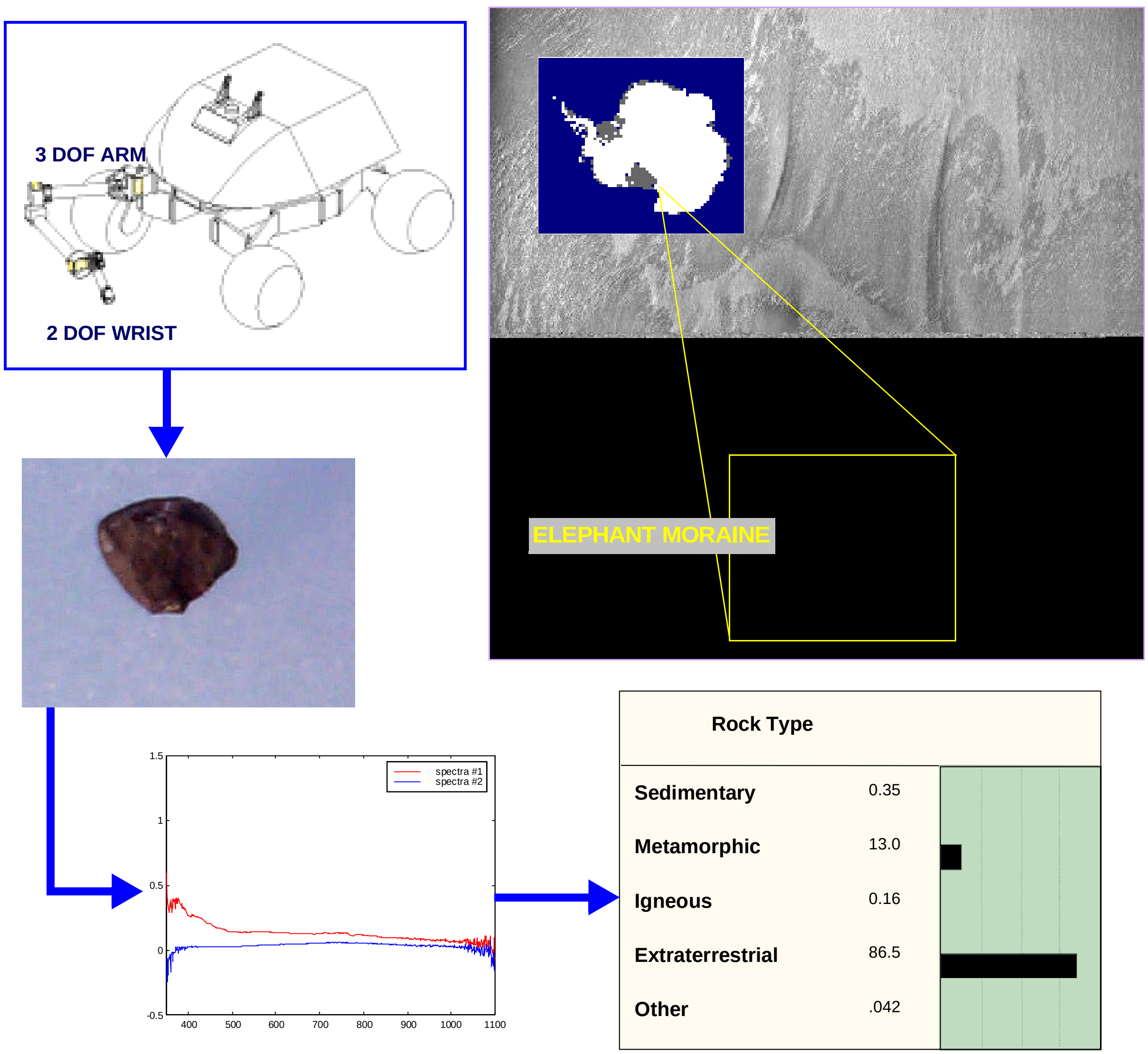

FIGURE 4: Robotic meteorite discovery: Imagery, spectra, and metal detection data will be analyzed by Nomad's Bayes-network based classifier to assess the likelihood of whether a sample is a meteorite or a terrestrial rock.

4. Deliverables, Schedule, and Budget

Surface System Thrust

Robotic Search for Antarctic Meteorites

Product Milestones	**Product Performance Achievement**	**Significance & Impact of Product to Missions**
FY 00 LEVEL 1 Milestone	Discover and classify Antarctic meteorites with an autonomous science robot in an environment and exploration scenario analogous to missions to the poles of the Moon and Mars.	This demonstration will advance planetary science through robotic discovery of new meteorite samples and autonomous geological characterization of hundreds of rock samples. This program offers an early demonstration of autonomous robots for planetary missions such as Robotic Outposts for In-Situ Measurement and Communication and Robotic Outposts for Heavy Duty Science Operations. This program will augment human search for Antarctic meteorites through intelligent coverage search of an area and in-situ classification of samples. In this context, this program is relevant to robotic missions precursory to HEDS.
FY 00 LEVEL 2 Milestone	Demonstrate Science Autonomy, a novel control architecture for science rovers. In the context of the 2000 Antarctic demonstration this program will validate: * High-level mission planning for navigation and science * Patterned search for optimal area coverage and power utilization * Safeguarding autonomy for navigation in polar environments * Bayes network for classification of science data acquired from multiple sensors * Visual servoing and fine placement control of science instruments	Science Autonomy is the core robotic capability to achieve autonomous search for Antarctic meteorites and scientific exploration of a region. Science Autonomy is the first robotics architecture with integrated mission planning with science goals, advanced techniques for intra site exploration, and autonomous real-time science data classification. The effectiveness of the search and autonomous in-situ science relies on the seamless interaction of Science Autonomy's control modules.

ITEM	**COST**
Personnel	
Salaries	380,609
Fringe Benefits	63,918
Operating Expenses	
Computing/Licenses/Supplies/ Copying/Publishing/Calls	63,731
Travel	40,000
Equipment	
Antarctica 2000 Expedition	170,000
Capital Equipment	25,000
CMU Overhead	256,742
TOTAL	1,000,000

PERSONNEL
0.4 x Principal Invest.
0.75 x Scientist
1.0 x Sr. Research Engineer
2.0 x Research Engineer
0.2 x Technician
0.75 x Lab Coordinator
2 x RI Grad Student
2 x Undergraduate
(9 FTE)

5. Intended Users:

The proposed tasks target future applications in Space Science Enterprise's Solar System Exploration program (S3-Requirements), with important applications to autonomous and human-assisting robotics for Human Exploration and Development of Space (HEDS) Exploration (H3-Requirements) and Human Life Science (H4-Requirements).

6. Research Team

- Funding Agency: NASA Cross Enterprise Technology Development Program (CETDP), Surface Systems Thrust Area.
- Funded Organization: The Robotics Institute, Carnegie Mellon University. Expertise includes perception and navigation for planetary rovers, sensors for modeling/ navigation/science, robot electromechanisms for field applications. Program PI is Red hittaker and Project Manager is Dimi Apostolopoulos.
- Supporting Organizations:
  - University of Pittsburgh, Dr. illiam Cassidy, foremost expert on Antarctic meteorites, 15 seasons in Antarctica, leader of the team that discovered ALH84001.
  - NSF ANSMET Program and Case estern Reserve University, Dr. Ralph Harvey, Leader of ANSMET S058.
  - Office of the Curator, NASA Johnson Space Center, Houston, TX, Dr. Marilyn Lindstrom, Lead officer at the Meteorite Curation Laboratory.
  - National Science Foundation, Office of Polar Programs: Expedition logistics and field support.

7. References

[1] Montemerlo, M., "UPN 632 Cross Enterprise Technology Development Program (CETDP): NASA Enterprise "Level 1" Technology Requirements," Presentation Slides, May 1999.

[2] http://www.frc.ri.cmu.edu/projects/mars/

[3] http://www.bigsignal.net

[4] Pedersen, L., Apostolopoulos, D., Whittaker, W., Cassidy, W., Lee, P., and T. Roush, "Robotic Rock Classification Using Visible Light Reflectance Spectroscopy: Preliminary Results from the Antarctic Meteorite Search Program,"Proceedings of the 30th International Lunar and Planetary Science (LPSC) Conference, Houston, TX, March 1999.

[5] Moorehead, S., Simmons, R., Apostolopoulos, D., and W. Whittaker, "Autonomous Navigation Field Results of a Planetary Analog Robot in Antarctica," 1999 International Symposium on Artificial Intelligence, Robotics and Automation in Space, Noordwijk, Holland, June 1999.

[6] Notes by Ralph Harvey, Head, Antarctic Search for Meteorite Team

[7] Apostolopoulos, D., Wagner, M., and W., L., Whittaker, "Technology and Field Demonstration Results in the Robotic Search for Antarctic Meteorites," Proceedings of the 1999 International Conference on Field and Service Robotics, Pittsburgh, PA, USA, August 1999.

[8] http://www.frc.ri.cmu.edu/projects/meteorobot