This project develops robots for autonomous search of Antarctic meteorites and demonstrates advanced technologies of perception, control, navigation, and scientific search in Antarctica, as a terrestrial analog to robotic exploration of Mars and the Moon. Carnegie Mellon University leads the research and demonstration of robots and technologies of the Robotic Antarctic Meteorite Search. The project is funded by NASA’s Telerobotics Program.

On the current expedition, Nomad will seek out and classify meteorites in the Patriot Hills region of Antarctica. In January 1998, an expedition to Antarctica validated robotic component technologies and meteorite detection sensors, including a panoramic camera, ground penetrating radar, metal-magnetic sensors, and an optical reflection spectrometer. The project expedition will demonstrate these technologies as Nomad autonomously detects and classifies Antarctic meteorites.

1. Fall 1998 Antarctic Expedition

The primary demonstrations for this year’s expedition are the robotic search for and classification of rocks and meteorites and the autonomous navigation of polar terrain. The primary demonstration will evaluate the robot’s classifier in distinguishing and characterizing rocks and meteorites using high-resolution imagery and optical reflection spectroscopy. The second demonstration aims at field evaluation of newly developed autonomous capabilities, including navigation with stereo vision and laser sensors, patterned coverage planning, and "blind autonomy." Additionally, the field team will evaluate a landmark-based navigation system, a millimeter wave radar, Nomad’s locomotion on ice and snow, and a communications architecture.

Figure 1: Artist’s conception of Nomad at a Patriot Hills ice field

A field team from Carnegie Mellon University, NASA Ames Research Center, and the University of Pittsburgh will reestablish a base camp at approximately 80 deg 18’ South - 81 deg 16’ West, and will operate there for six weeks. Field operations will take place between November 1 and December 15, 1998. The Chilean Air Force and the Chilean Antarctic Institute provide transportation and logistical support. Both Chilean organizations will participate with scientists and field experts. A research scholar from France’s LAAS-CNRS will evaluate stereo vision and laser perception sensors.
1. Primary Demonstrations

1.1 Robotic Search for Meteorites

The purpose of the December 1998 Antarctic field season is to test the autonomous meteorite classifier under true field conditions. Nomad will acquire data from new rocks and classify them with limited human input. This will establish conclusively whether the current system (sensors and classifier) is practical for field robotic deployment, and its suitability for robotic meteorite search.

Nomad will explore the areas of Independence Moraine, the region where data and rock samples were acquired last season. Nomad will collect images and spectral data from new samples, and feed the information to its classifier for assessment. Physical samples will also be taken from each rock that Nomad examines in order to be analyzed by a field geologist on the team. Nomad's classifier output will be compared to the geologist’s analysis for validation of Nomad's capabilities.

Nomad will operate in meteorite search mode for this expedition, which allows either autonomous navigation or direction by the science operator. Nomad autonomously acquires panoramic images of the environment, and the science operator monitors those images. If there is an interesting region, the science operator can direct Nomad to the region, and, once there, can command Nomad to acquire a high-resolution image of a sample rock. Nomad enters this rock into the database and uses the image to classify the rock. If Nomad's initial classification is promising, meaning that the sample is likely to be a meteorite, then the field operator places a spectrometer directly onto the sample. Nomad then re-classifies the sample using the spectrometer data in order to determine if the sample is actually a meteorite. After the sample has been taken, Nomad will resume autonomous navigation from the point at which the initial pattern was broken. Data processing and classification analysis will be performed in real-time on-board Nomad.

A Bayes network based rock/meteorite classifier will be implemented from the visual imagery and reflectance spectra of rocks obtained in the field. The classifier is capable of identifying and discriminating between the various local rocks (mostly marble, limestone, granite, quartzite and some igneous rocks) as well as meteorites and subclasses thereof (achondrite, chondrite and iron meteorites).

Autonomous Classifier

Thus far, the best results have been attained using spectral data from the visible to the infrared portions of the light spectrum (350nm - 2500nm), in spite of significant variations due to cloud...
cover and other atmospheric variations that affect the quality of the spectra. If confined to the visible wavelengths only (400nm - 900nm), approximately 90% of rock samples and 90% of meteorites are correctly classified as either rocks or meteorites based on field results from last expedition. For the task of identifying rock types, approximately 5% of rocks are misclassified using spectral data, with limestone and marble being the most likely to be confused. This is not surprising considering they both consist of the same minerals.

The Patriot and Independence Hills regions of Antarctica are not believed to harbor meteorites. Therefore, an area will have to be seeded with meteorites in order to test the classifier utility for meteorite search. A geologist looking at high-resolution images returned by Nomad will designate possible candidates for Nomad’s classification. In addition, Nomad will gather more data for use in further perfecting the classifier. There will also be an expedition further inland from Patriot Hills, to the polar plateau. There, human investigators will search for meteorites with a hand carried version of the same spectrometer Nomad is equipped with, and a digital camera. This expedition will be an opportunity to acquire more data from different geographical areas, particularly ones where meteorites may be found.

**Science Interface**

This season, a human operator will control the prototype meteorite search system. Therefore, a user interface has been created that allows control and testing of nearly every component in the science system. Although it can track the status of most science system components, the final implementation of the user interface deals most directly with three systems. First, the user can control the mission planner by specifying a robot task mode: go to a waypoint, execute a coverage pattern, or take sensor measurements. The user can also control the details of how the mission planner will coordinate the science system, such as setting way-point tolerance, robot field of view, and coverage pattern type. The user interface also allows access to the database. While the interface does not require the ability to update data into the database, the user needs to be able to look up information in the database such as target images or classifier probabilities. Finally, the user must control the pan/tilt camera to select new rock targets. This is one of the most critical functions of the interface. It has the ability to pan, tilt, and focus the camera until an acceptable initial, or "template", image is taken. The user clicks on the target in the template image, and the pan/tilt software inserts this data into the database. Then, the user is prompted to select a high-resolution image of the same target. The user can zoom well into the target to get a close-up image of it. This image, along with other information, is then inserted into the database for the classifier to use.

- **Autonomous Navigation of Polar Terrain**

The autonomous navigation system will be vigorously tested and run under various polar conditions. The testing of the system’s perceptual sensors will be the primary focus of the autonomous navigation assessment. Additionally, Nomad’s "blind autonomy," which is the ability to detect and recover when the robot is too close to another object, and new advances in Nomad’s patterned coverage search will be assessed.

Nomad’s performance will be evaluated on the four major terrain types present at Patriot Hills: blue ice field, snow, moraine, and sastruggi. The testing of the stereo vision and laser sensors on these terrain types will be particularly important, as Nomad has never traversed terrain of these types. The effects of and need for filters, particularly polarizing, on the stereo cameras will also be a major part of this testing.

In Nomad’s navigation system’s Antarctic configuration there are two types of perception sensors, stereo vision and laser sensors. Each sensor independently takes in the appropriate data and creates a map. The maps are grids where each cell contains two important pieces of information, a goodness value and a certainty. A goodness value is a rating of how beneficial it is for Nomad to be in that particular position, and a certainty is the sensor’s confidence level in the
data. These maps are then passed to Morphin, a program which merges them and determines which direction will provide the maximal goodness. There are two primary benefits to this methodology that will allow this system to be adapted for use in another context, potentially space exploration. The first is that it allows for the easy addition of other sensors to assess other factors in the environment. The second is the versatility of the goodness value. The goodness value can be adapted to evaluate any number of measurements, including science value and solar availability. These features will allow the technologies being developed in this expedition to be easily applied to robotic space exploration missions researching a variety of topics.

"Blind autonomy" is a new feature of the navigation system that evaluates Nomad’s ability to determine when it is too close to an object to turn away. Nomad also monitors motor currents and angle sensors to determine if it is traversing dangerous ground. This ability is very important in Antarctica where the functionality of stereo and laser on ice fields is not known. Blind autonomy allows both monitors to call a backup and turn maneuver to recover from the problem.

A special form of autonomous navigation will also be evaluated this year involving patterned coverage. In patterned coverage search, the operator will define a polygonal area to cover and the pattern to use. Nomad then follows that pattern in order to maximize the coverage of the area. While Nomad travels, the operator is able to select an object of interest from Nomad’s panoramic view and enter it into the database. The operator can also command various sensor readings be taken. Nomad will execute these commands even if they require deviating from the initial pattern because the maneuver or path planner can create a route to the region of interest. When the measurement is complete, Nomad will resume the initial pattern, and return to the point from which it left the initial pattern and continue its autonomous traverse.

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Figure 3: Meteorite search and autonomous navigation demonstrations will be performed in the area between Patriot and Independent Hills.
1.2 Technology Experiments

- **Landmark Based Navigation:**

  Landmark based navigation is intended to greatly improve robot position estimation over dead reckoning by tracking visual features in the environment and using them as landmarks. This measurement returns bearing to the visual feature only. No prior knowledge regarding the position of the landmarks assumed, so the problem is one of simultaneously mapping and localizing. This is analogous to being placed in an entirely unknown environment and using the existing environment to localize while building a model of the environment.

  During this field season, the project will use visual tracking software to process a sequence of panoramic images and store the bearing to each visual target in each frame over the sequence. In addition, the project will process telemetry logs and extract steering encoder and wheel encoder values. The project will then use various estimation methods, such as Extended Iterated Kalman Filter, Covariance Intersection, and others, to localize the robot.

  The current hardware configuration for landmark based navigation consists of a panoramic camera connected to a framegrabber on board a dual-Pentium PC mounted on Nomad, as well as wheel encoders and steering encoders on Nomad’s chassis. The PC will be used to log images directly from the framegrabber, and to log NDDS messages containing telemetry while Nomad drives on the ice. Telemetry and images will be processed off-line to produce mapping/localization results.

- **Millimeter Wave (MMW) Radar**

  MMW radar is a preferred imaging sensor modality because it provides precise range measurements for the environmental imaging needed to perform autonomous operations in dusty, foggy, falling snow occluded (white out, blizzard) and poorly lit environments. Back scatter test will measure the energy reflected in a direction opposite to the incident wave. This test will explore the energy returned at different grazing angles and on different surface types (blue ice, flat ice and snow). These results will be compared to the performance on a similar geometry of regular dirt. This data will help to build a database of performance of MMW imaging radar on different terrain.

  Atmospheric penetration test will measure the degradation of performance of the sensor under severe visibility conditions. The same scene will be sensed under clear air conditions and also under heavy flying snow (whiteout, blizzard). Visual conditions will be recorded by photography of the scene. A laser scanner will scan the same image for comparison purposes. A quantitative estimation of performance in severe polar vision conditions will support the application of this sensing modality.
1.3 Communications

The communications system in Antarctica involves the INMARSAT network. INMARSAT is a communication satellite network. A solar powered INMARSAT terminal will sit at a hilltop location in the Patriot Hills to transmit data and voice to the United States. This terminal will also receive telephone calls with an answering machine, allowing the terminal to be unmanned. The hilltop box will also house a router, ARLAN, power inverter, power regulator, and a battery. The ARLAN allows wireless ethernet communications from the operations tent to the hilltop router.

To turn on the communications link, one needs to telnet to the router from any computer on the local network and initiate a phone call from the INMARSAT terminal to the United States. About a minute later, all the computers in Antarctica can talk to all the computers on the SCS network at CMU.

This satellite link will be used approximately every hour or as needed to transmit new high resolution images of rocks, spectrometer data, classification results, and telemetry to send to the web server at CMU.

Figure 4: Communications architecture.
2. Schedule

2.1 Primary Dates

<table>
<thead>
<tr>
<th>Dates</th>
<th>Activity</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept 26</td>
<td>Fuel available for ice deployment</td>
<td>Provided from local fuel distributor</td>
</tr>
<tr>
<td>Oct 25</td>
<td>Equipment to Punta Arenas</td>
<td>Clear customs in Santiago Airport. FACH C-130 to Punta Arenas.</td>
</tr>
<tr>
<td>Oct 23</td>
<td>Field Team departs from Pittsburgh</td>
<td>Air to Santiago. Two days for public relations. Air to Punta Arenas.</td>
</tr>
<tr>
<td>Nov 1</td>
<td>Team and equipment ice deployment</td>
<td>Air from Punta Arenas to Patriot Hills. FACH C-130. Weather permitting.</td>
</tr>
<tr>
<td>Nov 1-8</td>
<td>Operations at Patriot Hills</td>
<td>Initial tests and activities near Chilean Camp. Side flight to south locations.</td>
</tr>
<tr>
<td>Nov 9-29</td>
<td>Operations at Nomad Valley</td>
<td>Formal tests and experiments. Last preparation for intercontinental communications.</td>
</tr>
<tr>
<td>Nov 30-Dec 6</td>
<td>Endurance traverse</td>
<td>Nomad drives from Nomad Valley to Chilean Camp.</td>
</tr>
<tr>
<td>Dec 6-10</td>
<td>Packing and camp break.</td>
<td>End research activities. Break camp and prepare to return.</td>
</tr>
<tr>
<td>Dec 10</td>
<td>Return to Punta Arenas</td>
<td>Public display of Nomad in Punta Arenas.</td>
</tr>
<tr>
<td>Dec 15</td>
<td>Equipment departs, Team breaks</td>
<td>Santiago (FACH C-130). Clear customs. Air to the USA.</td>
</tr>
</tbody>
</table>

2.2 Expedition Activities

All of the major technical tasks are underlined

**Week 0: Punta Arenas**

Week 0 corresponds to the days previous to the ice deployment. Punta Arenas is a resourceful city and the field team will acquire goods there. The team is briefed on the particulars of a deployment by the Chilean Air Force.

- New Members Expedition Briefing (1). (All, FACH, INACH) The group briefs the expedition plan to members joining the expedition team in Punta Arenas.
- Antarctic Deployment Briefing. (All, FACH). Chilean Air Force briefs the team on safety aspects of the deployment of the team on ice.
- Photoshoot (1). (All) Nomad and all team members are taped and photographed. Materials are prepared to send to USA from Punta Arenas.
- Last Predeployment Check. (All) Nomad is completely assembled and tested after travelling from the USA. Local acquisition of fresh foods, expedition items, and personal items.
- Public Relation Activities. (All) Promotion to local press and international press in the area. Presentation to local universities and to the local authorities.
- Contingency Plan. (All) Take action on the report of the status of equipment left at Patriot Hills on previous expedition. Initiate acquisition of missing items and equipment.
**Week 1: Camp Set-up and Robot Tests**

The main activities will be the communications setup and testing, selection and preparation of main operation and testing site, and the side search expedition. The week finalizes with the transportation of Nomad and all facilities to the Nomad Valley.

**Initial Stereo Calibration.** (Stewart, FACH helps). The team assembles the calibration cube and calibrate the stereo cameras. Place: near the camp. Duration: 1 day.

**Navigation Demonstration (1).** (Sib, Stewart, Alex) Nomad traverses an area planted with obstacles to test stereo contrast on ice/snow. Nomad traverses 1 km. Place: near the camp. Duration: 1 day.

**Nomad Mobility Test.** (Mike, Sib, Stewart, FR1, FR2) First tests on the snow/ice and on the response to temperature variations. Place: surroundings of Chilean camp. Duration: 2 days.

Temporary Camp Setup: (all, FACH help) The team sets up the temporary camp at Patriot Hills Place: near the Chilean camp. Duration: 1 day.

Expedition Briefing (2). (All) Group briefs on planned activities to Camp Chief. Joint participation is specified and all members are introduced to each other.

Side Search Expedition. (Bill, Pascal, Liam, FEx1, FEx2) Prepare and depart for meteorite search expedition. Place: Pirrit, Nash, Martin Hills. Duration: 5 days.

Satellite Communications Setup and Testing: (Sib, Matt and Alex, ChM) Test Satellite communications (voice, data). Where: Chilean camp. Duration: 1 day.

Relay Station Setup and Testing. (Sib, Matt, Alex) Setup ethernet and VHF relay station. Test coverage of VHF and ARLANS.

Main Operations Site Selection. (Sib, Matt, Ben, Stewart, Alex) Visit to Independence Moraine. Visit to Morris Cliff Moraine. Duration: 1 day.

Main Operations Site Preparation. (All) Ferry supplies, tents, equipment and Nomad to selected site. Setup Office, Shop, Power Station and personnel facilities. Place: selected main operations camp. Duration: 2 days.

Photoshoot (1). (All) Nomad and all team members are taped and photographed. Material prepared to send in the next plane.

Photography Flight. (Pascal, Matt, Alex, Nicolas, Others) 30 minute flight to take pictures and videos of the Patriot Hills Area. This occurs after the selection of main operation site. Duration: 1 day.

Selection of Best Route for Towing Nomad. (FEx1, Mike, Alex) Two alternative routes are explored and safest route is marked. Duration: 1 day.

Other Routes Marking. (Matt, FEx1, FEx2) All common routes are marked in preparation for white outs. Poles every 100 m. and distance indicators. Duration: 2 days.

**Weeks 2-3-4-5: Field Work**

This week starts with the full setup of the Nomad-Control Sled-Repeater Station and Satellite Station. Various preliminary tests are performed. The general motion goes from the north side of the moraine towards the east, and then back at the other side of the moraine where a variety of areas and obstacles can be found.
Robotics Rock Classification (1). (Liam, Stewart, Sib, Alex) The first science demonstration activity tests the search pattern in a small area with sparse rocks (that will not pose a complex problem to navigation). Place: north side of Independence Hills Moraine. Duration: one day.


Landmark Based Navigation (1). (Matt, Stewart, Alex) Navigation is tested in an area with high density of rocks. Automatic landmark tracking is demonstrated. Duration: one day. Place: eastern extreme of moraine or any place at the south side.

Intercontinental Communications Test. (All) The whole communications scenario is tested to CMU quarters. Images are transmitted to the USA from the Nomad. Duration: one day. Place: south side of Independence Hills Moraine.

MMW Radar Imaging. (Alex, Matt, Stewart) Mapping of area with various obstacles. Study of grazing angle vs. energy return. Use of bad weather for repeating the experiment. Duration: 1 day good weather, half day white out.

Mobility Test (1). (Sib, Stewart, Alex) First part of the Mobility Test in flat ice. Place: north side of Independence Hills Moraine. Duration: half day.

Full setup test. (All) Full test of Nomad control, data transmission, driving and path search. Place: North side of the Moraine. Duration: 1 day.

Regular Ferry. (Two members by turns) One trip approximately every other day to the Chilean Camp to resupply food and check the repeater station. THis pattern continues until the camp breaks.

Selection of Science Site. (Liam, Stewart, Alex) Explore and characterize the demonstration site for the autonomous rock classification. Define and identify the area and borders. Obtain visual data to build the site information database.

Photoshoot (2). (All) Nomad and all team members are taped and photographed. Material prepared to send in the next plane.

**Week 6: Endurance Test, Camp**

First Endurance stage. (All) Nomad drives from Moraine Camp to the East side of Patriot Hills.

Second Endurance stage. (All) Nomad drives from the East Side of Patriot Hills to Chilean Camp.


Moraine Camp Break. (All) Moraine camp is dismantled and tents are setup near the Chilean Camp.

Route Indication Pull Out. The route markings are retired and stored.

Inventory and Packaging. (All) The expedition equipment is inventoried and packaged. Boxes are numbered and marked.
Patriot Hills Camp Break. Upon the arrival of the pull out fight, the Patriot Hills Camp is dismantled.

Week 7: Post-Expedition Activities at Punta Arenas

First Open Report. (All) Team is back from Patriot Hills. Interviews and reports are broadcast over the Internet to the USA, along with early results from the expedition.

Nomad Display. (All) Nomad is displayed on the Main Square of Punta Arenas. Team presents results, videos, and distributes fliers. Duration: 2 days.

Packaging Check. (All) Team checks and seals packages.

Nomad Dismantling and Packing. (All) Nomad is prepared for shipping it back to the USA.

Team break. (All) The team realizes the last joint activities.

2.3 Contingency Plan

Each contingency plan lists the reason, changes in the place operations, change in the activities.

No INMARSAT B. Send INMARSAT Equipment back to the U.S.

No Repeater. Weeks 2,3&4 at Morris Cliff Moraine. INMARSAT B in the Computing Tent.

Nomad broken. Sensors are dismounted from Nomad. Manual deployment

Storm warning. Nomad is towed inside the Shop. Cancel field events and maintain written report.

No Equipment at Patriot Hills. Acquisition of missing items in Punta Arenas.

3. Other Information

3.1 Acronyms

CMU: Carnegie Mellon University, Pittsburgh, Pennsylvania, USA.
RI: The Robotics Institute, at Carnegie Mellon University
FRC: Field Robotics center, research center in the Robotics Institute
INACH: Chilean Antarctic Institute
FACH: Chilean Air Force

3.2 Places and Names

CMU Temporary Camp. North of Patriot Hills, near the FACH camp. Weeks 1 and 5 consists of Nomad Shelter, Computing Tent and Sleeping Quarters. Permanently has INMARSAT/INTELSAT, VHF and HF Communications in a FACH tent for continuous power (from the Chilean generator).

Main Camp. Camp close to the Independence Hills Moraine. Main operation facility for Weeks 2, 3&4. Connected to the main camp via a repeater at Windy Pass. This camp will hold 8 people. Ferry to main camp daily for fresh food, maybe every other day.
Windy Pass. High place on Patriot Hills accessible by snowmobile. Good candidate to setup repeater station.

Nomad Valley. Area between the Patriot Hills and Independence Hills. Place for most public activities, tests and experiments. The science demonstration occurs in this area as well.

Traverse Support Camp. Small number of tents to support the essential team that is following the Endurance Traverse.

3.3 Facilities

Sleeping Quarters: 5 North Face Expedition 25 for 10 people plus 1 North Face Expedition 18 for one more person.

Latrine: Tent with elements to comply with the international waste management regulations.

Power Station: Tent that covers the generator and fuel containers.

Nomad Shelter: Provides a closed shelter to protect Nomad in case of storms and white outs. It also has space for hardware work. Emergency place for sleeping.

Computing Tent: Provides most computing facilities ARLAN for all people to work. Connected to the mobile control tent by ARLAN (this link is not critical but useful to have). It is the multicolored Endurance tent.

Control Dome: Provides local control and relays to repeater station. Its purpose is to provide non interrupted control and supervision to Nomad.

Repeater Station: Includes back to back ARLANs and VHF repeater. Solar powered. Mounted at Windy Pass.

4. Field Expedition Members

Alex Foessel (CMU). Field lead, public relations, MMW imaging radar test.

Liam Pedersen (CMU). Robotics science, science record, meteorite search.

Matt Deans (CMU). Computing and communications, landmark based navigation experiment.

Stewart Moorehead (CMU). Navigation and autonomy, finance and operations log master.

Mark Sibenac (CMU). Nomad demo/tests coordinator, computing and communications.

Michael Parris (CMU). Mobility tests, filming record, camp logistics, Nomad maintenance.

Bill Cassidy (U Pitt). Meteorite search lead, written record


Nicolas Vandapel(LAAS, France). Responsible for independent experiment agenda.

Guest Investigator (FACH, Chile). to be assigned

Guest Investigator (FACH, Chile). to be assigned

Guest Investigator (INACH, Chile). to be assigned