Cool Robots: Scalable Mobile Robots for Instrument Network Deployment in Polar Climates

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INTRODUCTION

The Antarctic plateau is a unique location to study the upper atmosphere at high magnetic latitudes, providing a stable environment for sensitive instruments that measure the interaction between the solar wind and the earth's magnetosphere, ionosphere, and thermosphere. Existing stations on the edge of the continent and at South Pole, and six low-power (50 W) Automatic Geophysical Observatories, demonstrate the value of distributed ground-based observation of solar-terrestrial physics. Increasing the spatial density of these of these observations offers great scientific opportunities. The National Research Council Executive Summary emphasizes the need for mobile instrument networks by recommending "comprehensive new approaches to the design and maintenance of ground-based, distributed instrument networks, with proper regard for the severe environments in which they must operate. (NRC, 2002)"

This paper describes scalable mobile robots that enable deployment of instrument networks in Antarctica. The drivetrain, power system, chassis and navigation algorithms scale for payloads of roughly 5-25 kg. One can envision deploying robots from South Pole to desired locations on the plateau for long- or short-term observation, and retrieving or repositioning the network through Iridium-based communication. Potential missions include deploying arrays of magnetometers, seismometers, radio receivers and meteorological instruments, measuring ionosphere disturbances through synchronization of GPS signals, using ground-penetrating radar (GPR) to survey crevasse-free routes for field parties, and conducting glaciological surveys with GPR. Robot arrays could also provide high-bandwidth communications links and power systems for field scientists.

Based on this concept, a single robot is under construction to carry a tri-axial fluxgate magnetometer, an Iridium modem, and a modest set of weather instruments. A magnetometer serves as an important payload test case. Magnetometer arrays exist in low and mid latitudes, but polar regions provide the unique windows to observe the effects of the solar wind on the Earth's magnetosphere. With mobile networks, the potential exists to tune sensor locations to magnetosphere events. Also, synchronized data from polar networks offers the potential to discover spatial characteristics of narrow-band spectral features in geomagnetic field data, identify magnetospheric boundaries, and refine models accordingly (Lanzerotti et al., 1999).

Remote observatory deployment on the Antarctic plateau via transport and small aircraft is expensive and entails hazards at remote takeoff and landing sites. For large-scale and widely distributed (>500 km radius) networks, relatively low-cost mobile robots can reduce per-instrument deployment cost. Semi-autonomous network deployment would also free limited aircraft and human resources for other missions.

Harsh weather of Polar environments, long-range requirements, navigation issues and variable terrain pose significant design challenges for inexpensive unmanned vehicles. Instruments will be deployed for long periods in drifting snow and must have a stable environment with low vibration and electromagnetic noise. Robots and deployed sensors should be retrievable with high reliability to minimize environmental impact and cost. This paper summarizes related robotics research and outlines mobile robot design concepts for Polar environments, technical challenges associated with their development, and enabling technologies for cost-effective mobile robots.

STATE-OF-THE-ART ROBOTS FOR EXTREME ENVIRONMENTS

Carnegie Mellon University developed NOMAD, a gasoline-powered robot for polar and desert environments (Nomad, 2004, D. Apostolopoulos et al., 2000). The 2.4x2.4x2.4-m, 725-kg NOMAD (Fig. 1) can travel up to 50 cm/s and can deploy instruments such as a magnetometer. In 1997 NOMAD executed its first mission in the Atacama Desert of southern Chile, traversing 223 km through tele-operation. Subsequently, NOMAD successfully found and classified five indigenous meteorites on an Antarctic mission. For our purposes, NOMAD's large size, cost, and non-renewable fuel are disadvantages. Its deployment experience suggests that navigation cameras may work poorly in polar climates due to reflection of sunlight off of the snowfield.

Fig. 1 NOMAD – CMU/NASA gasoline powered robot, from Nomad, 2004. Used by permission

Spirit and Opportunity are Mars Exploration Rovers from NASA/JPL. Each 2.3x1.6x1.5-m rover weighs 174 kg and has a top speed of 5 cm/s (NASA/JPL, 2004). The power source is a multi-panel solar array and two rechargeable lithium-ion batteries, enabling the rover to generate 140 W of power for four hours per sol, when the panels are fully illuminated. The Warm Electronics Box, with batteries, electronics, and computer, cannot exceed -40°C to +40°C. Gold-painted, insulated walls, solid silica aerogel, thermostat and heaters, and a heat rejection system protect the body from 113°C temperature swing during the Mars day. The payload includes a panoramic camera, miniature thermal emission spectrometer, a Mössbauer Spectrometer, Alpha Particle X-Ray Spectrometer, and a rock abrasion tool. Each of the six wheels is driven by its own in-wheel motor, and the two front and two rear wheels have steering motors for point turns. The rovers are well suited for their Mars mission, but are not economically viable for instrument-network deployment.

Fig. 2 Hyperion rover, from Hyperion, 2004. Used by permission.

Hyperion (Fig. 2) is designed for sun-synchronous exploration (Hyperion, 2004, Wettergreen et al., 2001). The 157-kg, 2x2.4x3-m vehicle includes a 3.45-m_ nearly vertical solar panel; its maximum speed is 30 cm/s. The chassis is intentionally simple - a 1.5 N-m, 150 W brushless DC motor combined with a harmonic drive for an 80:1 reduction ratio drives a wheel through a bicycle chain. A passively articulated steering joint provides two free rotations, enabling moderate maneuverability and mechanical simplicity. This design has many appealing features for instrument-network deployment, including renewable fuel, simplicity and potential for low cost.

Commercial all-terrain robots made by iRobot and ActivMedia come in sizes 39-100 kg carrying payloads of 7-100 kg. Powered by two DC servomotors and a 4-wheel differential drive system, these battery-operated robots run for 2-6 hours at speeds between 1-2 m/s. Without navigation instruments and software, these robots cost from \$7,000 to \$22,000. Though the potential exists to retrofit these robots for solar operation, they are not designed for low temperature, and the solar panels alone could comprise the entire payload budget.

COOL ROBOT CONCEPT

Our design targets interior Antarctica, which is characterized by low snowfall, moderate winds, and extreme cold. We envision networks of robots, guided by GPS and on-board sensors that are launched and retrieved from South Pole Station during the austral summer. Key design issues are outlined in this section.

Fig. 3 Satellite Photo of Antarctica (USGS, 2004)

Figure 3 shows a satellite photo of Antarctica, with its vast central plateau consisting of over five million square kilometers of relatively flat, crevasse-free terrain. A second large area of operation is the Ross Ice Shelf. Generally, Antarctic snowfields consist of dense, strong wind-blown snow. There are few obstacles aside from wind-sculpted *sastrugi,* dune-like features that are identifiable on satellite imagery. The central plateau receives less than 50 mm precipitation (<500 mm snowfall) in an average year. During summer months at South Pole, wind speed averages 2 m/s (Valenziano and Dall'Oglio, 1999), the 5-year maximum speed is 20.5 m/s (CMDL, 2004) and the average daily temperature is –20 C to -40 C.

An Antarctic robot must traverse firm snow and occasional softer drifts, sustain mobility in windy conditions, minimize environmental impact, and operate in temperatures down to –40 C. We envision a lightweight, solar powered, wheeled robot capable being transported in a Twin Otter aircraft and capable of traversing 500 km within two weeks. After reaching a target location, the robot could collect data over a period of 2-3 months before returning to South Pole for winter. The concept comprises a low center-of-gravity vehicle with four direct-drive brushless electric motors, an enclosed thermally controlled volume for instrumentation and batteries, and a solar panel "box" for renewable energy. Table 1 provides design specifications for a wheeled robot, along with a price point that would provide economic viability of deploying networks of such robots.

Table 1 Robot Specifications

Maximum Speed	≥ 0.80 m/s
Mass (excluding payload)	≤ 75 kg
Payload Mass	≥ 15 kg
Ground Pressure	≤ 20 kPa
Operating Temperature Range	0 C to –40 C
Dimensions	≤ 1.4 x 1.15 x -m
Cost	≤ \$20000

Motion resistance in snow is attributed to sinkage, and is related to the strength of snow immediately in front of the driven element, the length of the tire or track in contact with the snow, and the tire or track width (Richmond et al., 1995). Sinkage should be small in the dense snow of the Antarctic plateau, given the target ground pressure (< 20 kPa). The estimated total resistance of 0.25 for a 90 kg vehicle requires a net traction force requirement of 221 N. Travel of 500 km in two weeks requires an average speed of 0.41 m/s, giving an average power requirement of 90 W, and a maximum power of 180 W for the top speed of 0.8 m/s. Allowing up to 40 W for housekeeping power and power system efficiencies provides a target power budget of approximately 220 W.

Despite its harsh climate and low sun angles, Antarctica is ideal for a solar-powered robot. The summer sun provides a 24-hr energy source, and the central plateau receives scant precipitation and infrequent fog. The Antarctic plateau is nearly completely covered in snow, with albedo averaging 95% across visible and ultraviolet wavelengths (Grenfell et al. 1994) and fairly uniform scattering in all directions (Warren et al. 1998). The high altitude and dry air block less incoming radiation, and there is a small benefit due to proximity of the Earth to the sun during the summer. The sun remains at approximately the same elevation throughout the day (especially near South Pole) resulting in relatively constant energy input. Low elevation angles and significant reflected solar energy indicates that nearly vertical solar panels are optimal. Also, solar cell efficiency increases as temperature decreases.

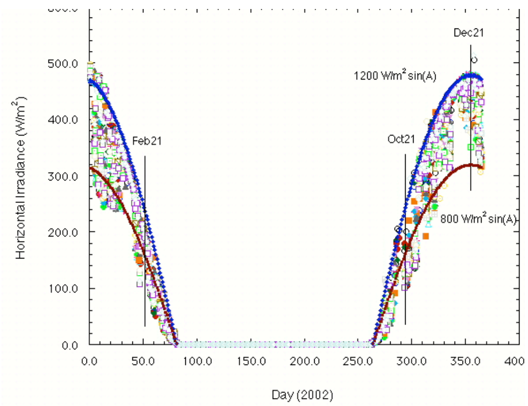

Fig. 4 Daily average horizontal insolation at the South Pole, 2002

Average horizontal insolation data for 2002, provided in Fig. 4, show a range of horizontal irradiance of 300 to 500 W/m^2 at the South Pole (CMDL 2004). Adjusting for elevation angle gives a net insolation between 800 W/m^2 and 1200 W/m^2, which is consistent with earlier studies (Hansen, 1960). At other Antarctica locations, where cloud cover and fog are more frequent, the average insolation is about half this, but the sunny days are almost as bright. For comparison, on a clear winter day in New England, at a sun elevation of 20 degrees, the total insolation is between 600 and 800 W/m^2. Table 2 summarizes insolation data at various locations on the Antarctic continent and elsewhere. The average solar energy input during the November to February operating window is approximately 1000 W/m^2, with an average sun elevation of about 20 degrees.

Table 2 Insolation for Various Sun Conditions

Condition	Nominal Insolation
Max. Antarctica continent	1200 W/m^2
Avg. South Pole, Nov-Feb	1000 W/m^2
Avg. South Pole, at solstice	1100 W/m^2
Avg. south polar plateau	> 800 W/m^2
Avg.Ross Ice Shelf	400 W/m^2
Jan 2004 measurements, Hanover, NH	660 W/m^2

For panel sizing, we developed a model to predict power as a function of solar insolation, sun elevation and azimuth for solar panels in a snowfield. The model assumes diffuse reflection from the snow at a specified albedo. We validated it using data collected with a commercial 20-W panel during Jan-Feb 2004 in Hanover, NH. Significantly, the top and side panels contribute as much power to the robot as the panel facing the sun. Figure 5 shows the resulting robot design concept – a wheeled chassis enclosed by a five-panel box – along with predicted panel capacities extrapolated from the model for nominal Antarctic solar radiation, 20° sun elevation, and 90% albedo. The panel outputs are reported as a percent their standard capacities (rated at 1000 W/m^2 insolation). The front panel (directly facing the sun) has a capacity of 128%, which exceeds 100% due to reflected energy.

Even the back panel receives substantial radiation, as the robot's shadow is not as large as the effective area of snow that reflects light to the panel.

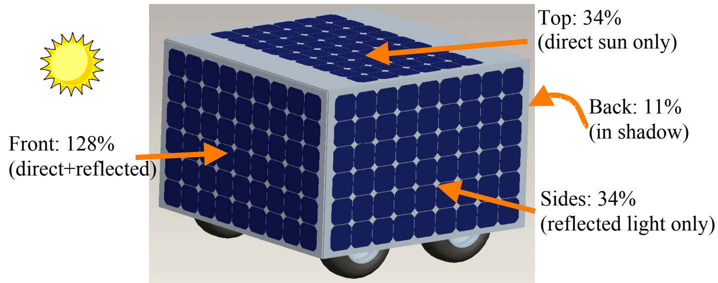

Fig. 5 Panel Power Capacities in Nominal Antarctic Sun

Enabling technology for the robot are the affordable, 20%-efficient A-300 solar cells by Sunpower, Inc., which became available in 2003. Figures 6 and 7 show predicted power available to the motors for a robot using 54 of these cells per panel (each cell is 12.5x12.5 cm) at 1000 W/m^2 insolation and 90% albedo. The resulting robot will fit within the Twin Otter cargo bay. These results include efficient maximum-power-point-tracking circuits for each panel and subtract housekeeping power. The robot can drive at full speed even in below-average insolation. Under minimal insolation, there is enough power to drive slowly or charge the batteries and drive in short bursts on battery power. Diffuse incoming radiation – light scattered by the atmosphere – is an unmodeled benefit, as diffuse light is received normal to the panels from all directions. The total diffuse radiation is expected to be 50-100 W/m^2 (Hansen 1960) providing 40-80 W, enough to drive the robot in bursts and maintain instrument operation.

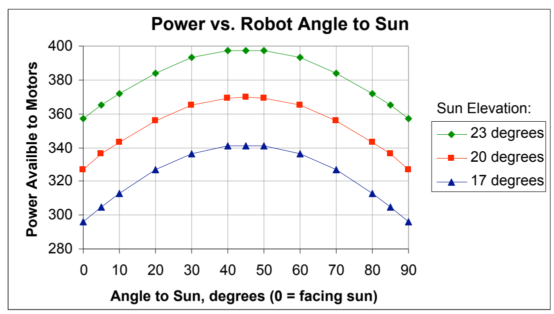

Fig. 6 Power available vs. robot angle-to-sun and three sun elevations

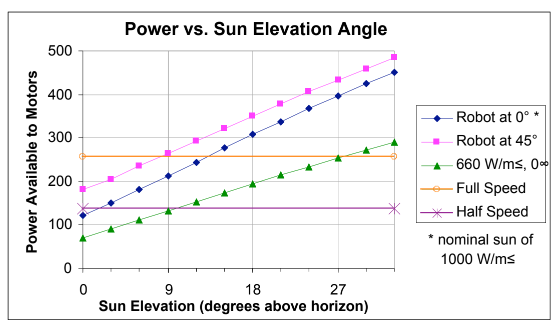

Fig. 7 Power Available and required vs. Sun Angle

A positive feature of navigation to deploy instruments on the Antarctic plateau is relatively flat, straight paths and hard snow, which minimize path planning complexity. For such paths, among the most promising navigation architecture is 'mixed-mode' operation (Simmons et al., 1995), which mimics human behavior, e.g., in hiking a known path over a long distance. The global objective is to stay on the path. However, a local mode in which the hiker goes around unanticipated objects, e.g., downed trees, is in force for short periods, after which the hiker returns to the path. In the initial stages of this research, global navigation is being implemented, primarily through GPS and speed control, with sensors available to detect unbalanced wheel speeds and hence potential traction issues, and low bandwidth path correction algorithms to reduce "dither" around the path. In the traversal of long distances, GPS induced path deviations are tolerable. Traction control can be layered onto the basic global path-following algorithm, along with sensors for tilt and slip sensing. Local-mode navigation would be invoked if sensors detect extreme tilt or slip. Navigation and motion control are also tied to the power system: the robot will move along the path only when adequate solar power is available to do so. Under cloudy conditions, the robot will move under battery power if necessary to prevent drifting in, and under windy conditions, the robot may face a direction that minimizes drag and the potential for tipping. A vision system is not anticipated: sastrugi are visible on satellite imagery and can be avoided through route selection; lack of contrast in snow-covered terrain would make on-board navigation challenging and potentially expensive.

DESIGN EMBODIMENT AND ENABLING TECHNOLOGIES

We have attempted to minimize vehicle mass by using stiff, honeycomb composites for the solar panels and chassis and custom-designed wheel rims and hubs. This section highlights the enabling technologies and cost-design tradeoffs, concluding with an estimate of parts costs and mass for the prototype robot.

Due to their newness, complete panels are not yet available for A-300 solar cells. Moreover, traditional panel construction, with its steel backing, is not viable for the robot. Thus, we will construct the solar panels in-house, using _” honeycomb sandwich panels (Nomex core, fiberglass facing). An EVA-Tedlar or Silicon-Tefzel laminate will encapsulate the cells. Similar honeycomb composite will be used to make the chassis box (Fig. 8). Honeycomb panel construction and joinery is mature in the aerospace field, and these materials supply area densities of 1.4 kg/m^2 for solar panels and 2.5 kg/m^2 for chassis walls.

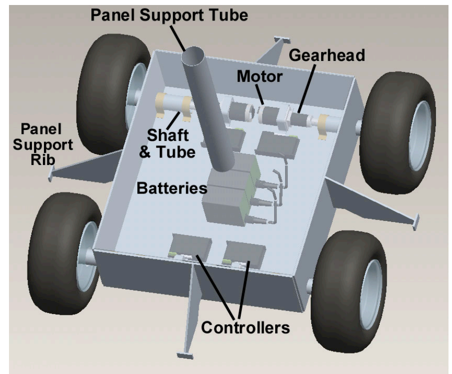

Figure 8 Internal chassis and components

Wheels are sized to provide adequate ground clearance and low rolling resistance. We considered many different tires, trading between traction, weight, pressure and rolling resistance. Due to availability and cost, a 16x6-8 ATV tire was selected for its low mass and traction. As low mass rims and hubs are unavailable for ATV tires, these were custom designed and machined in-house to meet the strength and deflection requirements for a 90 kg robot. For a mass produced robot, rims and hubs could be cast or stamped at low cost.

High-efficiency brushless motors with 90% efficient geartrains and lubricant for –50 C operation drive the wheels directly. Each motor has a controller that can be configured for speed or torque control. A single motor-gearbox combination underwent cold room testing within a box insulated as configured on the robot. Both long-term operation and start-stop operation indicate efficiency and controllability are maintained at cold temperatures.

The power system architecture includes three Lithium-Ion batteries in series and five solar panels, each of which can operate under varying insolation and temperature. To deliver power to a common power bus, each panel requires a maximum power point tracker (MPPT). These devices allow each panel to operate at the bus voltage established by the batteries, and meet power demands for the motors. Custom designed MPPTs under 250 gm each and in excess of 97% efficiency have been designed and constructed.

We estimate that the five-panel robot, without payload, will weigh ~73 kg with a total material cost of under $15,000. The design is relatively insensitive to payload up to about 20 kg. We will instrument the robot to assess our power-input and mobility models during field trials in Antarctica, anticipated for 2005-06 austral summer.

Conclusion

Solar powered mobile robots for operation on the Antarctic plateau are feasible from power availability, mechanical design, and power system design standpoints. Waypoint navigation on the relatively obstacle free plateau through GPS can provide long distance travel in timeframes that promote scientific missions envisioned. Mobile robots capable of reliable, long-term operation on the Antarctic plateau have the potential to enhance scientific research through instrument deployment, mapping, and providing portable, mobile power to field scientists.

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