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ABSTRACT

LORAX is a robotic mission to characterize the distribution of microbes in Antarctica's ice sheets. Robotic platform requirements include navigational autonomy and clean, sustainable power systems to operate unattended for a month without introducing contamination that would affect the results. This paper details the LORAX investigation, the navigational autonomy development and testing, and an analysis of wind and solar power to accomplish this mission.

1. Introduction

Ice sheets are of keen interest to astrobiology due to their potential to sustain and suspend organic activity. They are found in the polar regions of Earth and Mars and the surface of Europa. On Mars the polar layered deposits are promising targets for a search for organic material, dormant micro-organisms, and even seasonally-active microbial life.

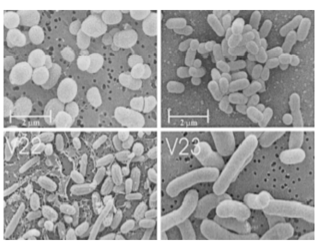

Figure 1 SEM images of bacteria from Vostok ice core at 3593m.

The Antarctic ice sheet is an excellent analogue to the Martian polar caps. Preliminary studies have shown that micro-organisms are present there at the surface (near South Pole Station) and 3.5 km below the surface (in the Vostok Ice Core). Abyzov et al. [1][2] and Poglazova et al. [4] showed that the Vostok ice core contained ~10^2 to 10^4 cells (detected by fluorescence) per gram ice throughout its depth. There was some evidence that the concentration of cells correlated with the dust concentration, possibly indicating source regions or mode of transport and deposition. Carpenter et al. [3] detected 200 to 5000 cells per gram of surface snow at South Pole. Sequence data indicates a collection of psychrophilic bacteria and one strain belonging to *Deinococcus*. DNA and protein synthesis indicates the possibility of metabolism at ambient temperatures of -12 C to -17 C. Price [6] has suggested that interconnected liquid water veins along grain boundaries might provide habitats for psychrophiles allowing for the maintenance of cells that that are metabolizing but not multiplying. Price and Sowers [5] have shown experimentally that microbial metabolic metabolic rates in ice decrease as exp(-U/kT) and are still detectable at a temperature as low as -40C.

Figure 2. LORAX robotic rover (Nomad) undergoing tests on frozen lake Mascoma, New Hampshire (February 2005), and searching for meteorites in Antarctica (January 2000)

However, relatively little is known about how the microbiology of the Antarctic polar plateau correlates over large distances. The studies discussed above have reported and characterized the presence and nature of microbial life at various depth levels in a few deep Antarctic ice cores and also in specific locations at the surface of the Antarctic plateau. But there is no "biogeographic map" of the surface of the Antarctic continent, one in which possible variations in the spatial distribution of microbial communities could be plotted against environmental parameters such as geographic setting, ice maturity, and exposure to surface elements

LORAX is a robotic survey of the microbial "bio-geography" of the ice around the Carapace Nunatak in Antarctica, seeking to determine concentrations and types of ice bound micro-organisms across a diversity of environmental conditions to infer the mechanisms underlying microbial preservation and habitats.

1.1 LORAX mission

The design of the LORAX investigation is driven by the following hypotheses that determine the requirements for the rover traverse route, sampling strategy and science payload:

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H1. The distribution of micro-organisms on the surface of the polar plateau surrounding a nunatak will vary considerably depending on the distance, wind direction and ice-flow direction to sources of bacteria. These sources include the marine environment, the nunatak itself, and other ice-free areas nearby.

H2. The concentration of micro-organisms will vary significantly between locations of accumulation (firn), flow (pack hard snow), and sublimation (blue ice).

H3. The concentration of micro-organisms on the surface (1 cm) of the polar plateau will be between 100 and 10,000 cells/g of ice.

H4. The selection effect of dry conditions and the UV flux at the ice surface will cause significant differences in the diversity and amount of micro-organisms at the surface of the ice and in the snow several centimetres below the surface.

1.1.1 Traverse Routes

To test H1 and H2 the investigation calls for a 30km circumnavigation of the Carapace nunatak, followed by a subsequent 100km traverse to and around another nunatak (Figure 3), evenly sampling the ice along each traverse.

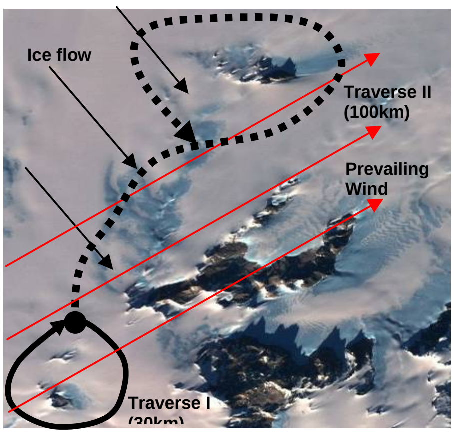


Figure 3 Traverse route cirumnavigating one of the Allan Hills Nunataks and the surrounding ice fields.

Carapace Nunatak is about 1 km in diameter and is located 10 km from the Allan Hills. The ice that completely surrounds Carapace Nunatak may be receiving microbes from several sources. Strong catabatic winds flowing down from the Polar Plateau could transport micro-organisms. If microbes are present on Carapace itself then the ice in the downwind direction might be enriched. Carapace Nunatak is 50 km from the dry valleys and coastal winds may occasionally carry micro-organisms from there as well as from the coast. As the ice flows toward a nunatak a stagnation zone is generated in the upstream direction. Here ice would be ablating and microbes in the ice may remain behind. Finally there may be deposition of microbes from the atmosphere. Note that the prevailing winds are orthogonal to ice flows, helping us to disambiguate ice transfer from wind transfer.

This route avoids potential crevasse zones, which are considered mission ending hazards.

1.1.2 Sampling Strategy

Samples must be obtained from at least 100 evenly spaced sites along each traverse, at each point characterizing the microbial population both within 1 cm of the surface and at 5 and 10cm depth to investigate the selection effects posited in H4.

This spacing is anticipated to be fine enough to resolve gradients in microbial populations. However since this sort of analysis has never been done before on the Polar Plateau we may find sites where the there are unusual or sharp gradients that merit more detailed examination. This motivates the requirement for in situ sample analysis to detect events that would merit re-sampling at a finer scale. Such events include: changes in the concentration of bacteria by more than a factor of 10 between two adjacent sites, evidence for a single sampling site that is more than a factor of 2 different from it closest neighbours (a notch in the distribution), extreme high or low concentrations compared to the ensemble of other sites.

In the event of slow progress, the policy is to reduce sampling rates in order to achieve the total traverse distance so as to obtain the desired wide area map.

1.1.3 Payload

This investigation requires the field detection and analysis of microbes in ice or snow at levels of 100 cells/g and measurement of both microbe concentrations and diversity.

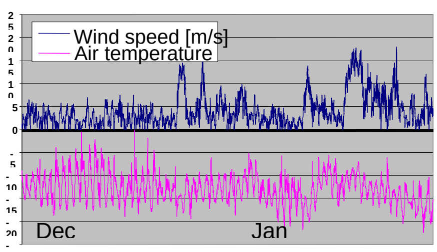
Microbes in ice can be detected, counted and categorized by examining their fluorescence emissions under various UV excitation sources. We are developing a UV fluorescence sensor to analyze single microbes in ice samples, retrieved by an ice-coring and sample handling mechanism (also under development) [7] that will retrieve samples from depths up to 10cm below the surface.

Both devices are housed in a single 1m x 0.5m x 0.5m box that is lowered onto the ground to sample and analyze the ice. The rover must remain in one place to do this.

Forward contamination of the site and rover by humans in the vicinity, and cross contamination between measurements are serious concerns whilst measuring such exceptionally low microbe concentrations. Furthermore, the UV instrument is acutely sensitive to soot from internal combustion engine emissions, which can overwhelm the signals from individual microbes.

1.2 LORAX Rover Design

The rover platform requirements derived from the traverse route, sampling strategy and payload are summarized as follows:

Traverse distance	144km (100km map distance + 20% map to odometric distance margin + 20% safety margin)
Terrain	Blue ice (50%), Hard pack snow (50%), with possible sastrugi (blown snow mounds). Mostly flat, with occasional 1 degree grades.
Hazards	Large sastrugi (snow mounds), but no crevasses.
Payload	2.8 hours are needed at each sample site. There are 100 sample sites.
Contamination	No contamination from gasoline or diesel exhaust permitted. Minimized or no human activity in vicinity of rover and rover traverse.
Logistics	All operations limited to summer field season (early December to late January). Traverse duration limited to 1 month, with 50% allocated as margin against inclement conditions.
Weather	24 hour sunlight, with clearness index 0.7, occasional complete white-outs. Temperatures typically between 0C and -20C, worst case -40C. Winds averaging 4-5m/s, very occasionally topping 15m/s. 

The LORAX investigation uses Nomad, an all-wheel-electric-drive vehicle with an actuated deployable chassis, electronically coordinated steering and articulated-frame averaging suspension. The power source is a 2kW gasoline generator. A large footprint and low center of gravity make Nomad a very stable platform that has been proven in Antarctic ice fields, snow and moraines [8][9].

Nomad's availability, mobility, proven performance and large payload capacity make it the platform of choice for this campaign. However, Nomad is currently unable to satisfy all the requirements. Key amongst these are the requirement for long duration unattended operations and a clean power source.

The next sections detail the development and testing of improved navigational autonomy, and an analysis of non-polluting long duration wind and solar power sources for the rover to satisfy the above requirements.

2. Navigation Autonomy

In the first stage of the LORAX project we undertook to provide Nomad with capability for full navigational autonomy. In its previous field deployments Nomad has employed limited obstacle avoidance while either being remotely teleoperated [10] or following fixed patterns of search [8].

We established a requirement that the rover should be capable of 10 km of autonomous traverse per day by reasoning that the available Antarctic field season would be about 4 weeks and in a bad year during 50% of the time inclement weather could affect operation, so 144 km in the remaining 2 weeks sets our upper bound at 10 km per day. The likelihood of this is low but with the navigational autonomy system capable of it, Nomad will be able to sprint 10 km in an (8-hour) day if needed.

For the LORAX investigation we equipped Nomad with binocular stereo cameras and a laser rangefinder (Figure 4). Previous studies [11] have shown that stereo vision fails with monochromatic images due to lack of texture and that laser scanning is confounded by falling snow and purely reflective ice. In our experiments we found that, barring white-out conditions, snow typically has enough texture from surface variation and lighting for stereo vision, ice is rarely a perfect mirror, and that median filtering and range gating eliminates most all false detections associated with falling snow.

Figure 4 Nomad is equipped with binocular stereo cameras, in sealed, heated enclosures, for dense range information in the near field. A single-axis, scanned laser rangefinder also swept a single line across the path to detect obstacles.

The strategy for autonomous navigation of planetary rovers that we have successfully employed in previous field systems including Hyperion [11] assumes planetary-like environment, specifically that the terrain is barren with obstacles either discrete objects (rocks) or topographic features like drainages, ridges, cliffs, and dunes, and operates without accurate global maps or localization.

The nature of the terrain encourages the use of an "optimistic/pessimistic" navigation strategy combining both stereo vision and laser scanning. Terrain that is unseen by stereo vision, for example due to occlusion or distance, is optimistically assumed to be traversable. The laser operates as a "virtual bumper" that stops the robot prior to collision when detecting obstacles missed by the optimistic evaluation, thus it acts as a pessimistic safeguard. In practice most of the terrain is eventually sensed by stereo vision and all is swept by the laser before it is traversed. This combination of optimistic and pessimistic strategies allows for efficient navigation with neither undue risk nor the need for perfect terrain knowledge.

3. Navigation Architecture

The navigation software that enables Nomad to drive autonomously was derived from the Zoë planetary rover currently in development for exploration in the Chilean desert. [12]. Additionally, algorithms to filter and interpret the laser scanner find there heritage on the Hyperion rover and have been validated in the Canadian arctic.

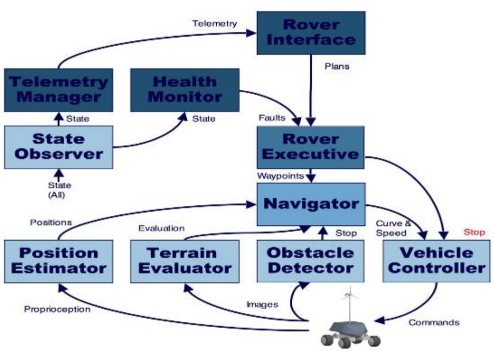


Figure 5 Software architecture for autonomous navigation employed on Nomad.

The navigation software implements several control loops growing from wheel servos, to gross vehicle commanding, then navigational guidance, and ultimately plan execution (Figure 5). The Navigator uses position estimate, an evaluation of near-field terrain, and lack of obstacles, to determine a commanded curvature and speed to reach a series of waypoints. The terrain evaluation, detailed in [11], applies metrics of slope, roughness, and discontinuity to estimate the smoothest path to the next goal. This path is commanded and then the evaluation begins again, cycling at 5 Hz for these experiments.

4. Field Experimentation

To validate our strategy for long-distance autonomous navigation in Antarctica we sought a suitable analog in a frozen lake surface of snow and ice and chose Lake Mascoma in New Hampshire. February 21-25, 2005, we deployed Nomad onto the lake for a series of experiments in mobility and power generation but primarily autonomous navigation. Description of our experiments and activities is available online at http://www.frc.ri.cmu.edu/projects/lorax/

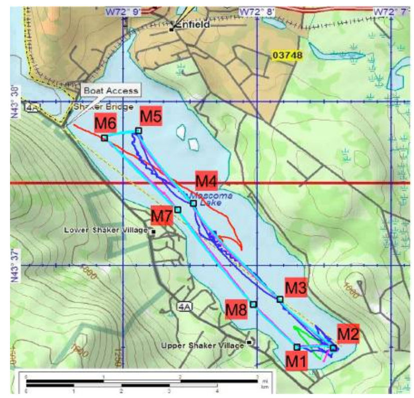


Figure 6. Map of Lake Mascoma with 5 days of rover traverse (overlay). Eight goal locations were selected, labeled M1 through M8, in a circuit of roughly 7km. The longest autonmous traverse (indicated in cyan) circumnavigated the lake circuit twice continuously for a total distance of 14km.

In five days of experiments Nomad drove 25 km autonomously modelling the terrain and avoiding obstacles as it navigated to each goal location. These experiments consisted of a number of short traverses to calibrate and tune sensors and evaluation algorithms. Considerable effort was taken to make the stereo vision algorithms robust to lighting conditions ranging from dim dawn and dusk to blazing mid-day. The traverses were dominated by a final endurance experiment of over 14 km executed continuously (Figure 6). The first 11 km employed on stereo vision but the final 3 km occur after dusk relied solely on the laser scanner to detect obstacles.

These experiments demonstrate that Nomad is capable of autonomously travelling the maximum daily distance we anticipate. They lend credibility to the assertion that a solar powered rover could autonomously execute the locomotion and science activities needed for the LORAX investigation

5. Power System

Nomad's current internal combustion engine power system, whilst supplying ample power, is unsuitable for the mission because of the contamination generated and the difficulty in carrying sufficient fuel for month long unattended operations.

Wind and solar power are promising options, but require a significant reduction in Nomad's current power consumption to be viable.

5.1 Locomotion Power Requirements

Because of mass (700kg) and size, locomotion dominates Nomad's power needs. Accurately modeling it is important to both determine mission feasibility and to redesign a more efficient drive train.

Critical to achieving the LORAX mission objectives is the optimization of Nomad's drive train. We developed an analytical model for power utilization as a function of speed, rover mass, terrain slope and rolling resistance.

Nomad's current locomotion system consists of a brushless DC motor, a Harmonic Drive (HD) reducer and a spur gear stage to drive the wheel, all housed within the wheel hubs. Power amplifiers and drive electronics are in the warm electronics box located within the rover body. Ackerman steering is accomplish with two additional brushless DC motors and harmonic drives.

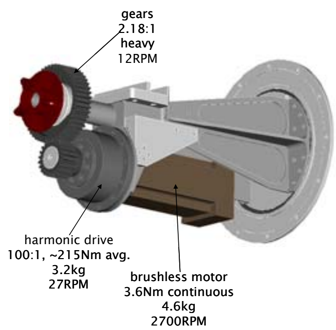


Figure 7 Nomad drive train

The model uses manufacturer data and experimental measurements to predicts power and torque dissipated at the wheels (for propulsion), the gear train and drive electronics (power only):

Table 1 : Predicted Nomad drive-train power dissipation	
Inputs	
Rover Speed	0.4 m/s
terrain slope	1 degree
Terrain Coeff RR	0.025 (snow)
Rover Mass	700.00 kg
Component	**Power Dissipated**
Terrain + Tires	
Terrain & tires	
Gears	
Seals	16 W
Spur Gear (2.182:1)	1.34 W
Harmonic Drive (100:1)	240 W
Electrical	W
Motor (mech + elec)	41 W
Amp	22 W
Total	437W

Field experiments were conducted to validate the model on different terrain types (below).

Figure 8 Nomad locomotion power tests and comparison with power model

TEST	Speed (m/s)	Avg. Power (W)	MODEL Power (W)
Test 4: f/b once	0.15	200	195.75
Test 5: f/b twice	0.30	300	291.50
Test 6: f/b 3x	0.45	400	387.25

Experiments included drive and steering on flat and inclined terrain and obstacle climbing, as well as zero-speed and no load tests with the rover jacked up to allow the wheels to run freely. Most experiments were carried on slag and gravel, and comparisons with analytical predictions were made for these materials. For all experiments, aggregate drive power was computed from current and voltage readings at the input of the drive amplifier. Overall, there is acceptable agreement between the model and field results (less than 3% deviation) especially in the cases that we managed to maintain steady state movement of Nomad over longer stretches of ground. This gives us confidence that the model will reliably to predict locomotion power draw for polar terrain.

Notice the high power dissipated by the harmonic drive. Even though HD offer excellent torque/size ratio, very-high single-stage reduction and zero backlash, they have a very high internal resistance that varies little with rpm and load. This makes them particularly inefficient under small load and low speed conditions. The no-load tests conducted with Nomad revealed that a single HD drew ~75 W to drive the wheel at the maximum speed of 0.5 m/sec. Moreover, the HD efficiency is dependent on temperature, a critical consideration for the LORAX project.

The second major source of power loss is the motor itself. A detailed load-matching analysis revealed that the current motors (Pacific Scientific brushless DC servomotors) are not suited for the speed/torque of the LORAX application. They are sized for a much broader speed range and have a flatter torque-speed profile than that required for the slow moving Nomad vehicle, that currently drives at 0.5 m/sec with the motor spinning at 2700 RPM.

Replacing the current drive motors and gearing with large diameter, multi-pole brushless torque motors with low ratio (5 or 7:1) and a planetary gearbox reduction units should improve significantly increase efficiency, and according to the model, reduce locomotion power consumption from 437W to 222W on a 1 degree hard pack snow covered slope.

5.2 Solar Power

Antarctica, despite harsh climate and low sun angles, is ideal for a solar powered robot during the summer season. There is 24 hr sunshine, little precipitation, moderate cloud cover and occasional fog. The snow and ice ground cover is highly reflective (95% albedo), scattering light uniformly in all directions.

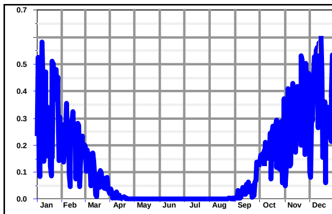
Nomad can support 4.1m^2 of solar panels with relatively little modification of the vehicle structure. We developed a simulation based mode to estimate the insolation incident on each panel as the rover navigates along its course.

Figure 9 Nomad solar panel configuration

NASA's Surface Meteorology and Solar Energy model [14] indicates the 10 year average solar insolation on a horizontal surface at Carapace Nunatak (76°53' S, 159 °24' E) is 6.3 and 5.2 kWh/ m^2/day for December and January respectively. This equates to daily averages of 262 and 217 W/m^2. By comparison, measured summer insolation at the South Pole is between 200 and 500 W/m^2, perhaps because Carapace's greater proximity to the ocean.

Typical solar insolation measurements, where available (no direct measurements are available for Carapace nunatak) are of aggregate insolation onto a horizontal surface. The direct and diffuse components must be inferred using empirically derived statistical models to determine the total insolation incident on an arbitrarily pointed panel. Our model uses the HDKR model [13] to predict total insolation on each of Nomad's panels as a function of rover orientation, local time, surface albedo and panel tilt. Synthetic hourly flat panel insolation values consistent with the aforementioned 10 year averages were generated using the National Renewable Energy Laboratory's Homer Software [13] for December and January and used to compute the optimal tilt angle and average summer insolation on each of Nomad's panels. These computations were done for the cases of Nomad remaining in an optimal fixed orientation (south) and adjusting its orientation every 3 hours. Note that Homer also implements the HDKR model (and was used to validate our software), but does not factor in the effects of a moving platform.

With the maximum rear-facing area (1.3m2) of Nomad covered in high efficiency (23%) but expensive (~$13k/m2) ATJ cells and the remaining areas covered with inexpensive commercial and less efficient (15%) standard silicon cells, Nomad generates 238W in a fixed orientation and 343W if adjusting orientation every 3 hours. Using only ATJ cells increases output to 302W and 404W respectively, but increases solar panel cost to $44k from $26k.



Simulated horizontal insolation	**Table 2:** Average summer solar panel insolation (W/m2)			
	Front	Rear	Port	Starboard
Fixed optimal orientation	338	366	358	349
Orientation periodically adjusted	327	771	343	327

5.3 Wind Power

Wind turbine considerations for powering a robotic vehicle include performance (power output as function of wind speed), over-speed control, susceptibility to mast motion, mass and wind load force.

Many land use turbines (such as the Bergey XL-1) cannot tolerate pitching of the mounting structure, for that reason turbines with marine variants (such as the Air-X) are favoured.

We considered a number of small (diameter less than 2.5m) wind turbines, eventually opting for the Air-X as an economical unit for initial tests (still ongoing) on the robot:

Average power production [W]	Wind speed (m/s)	Windseeker	Air-X	Air 403	XL - 1	TF 1803	F 910-3
December	3.1	19	8	8	31	14	5
January	5.0	51	27	27	99	47	14
December Doldrums	2.4	6	1	0	1	1	2
January Storm	9.0	133	77	79	293	136	35

Average power for the Air-X, mounted 3m above the ground, and accounting for the air density at the Carapace Nunatak altitude of 1946m, over the entire dataset in Figure is calculated to be 17W. However, actual performance is unverified and is expected to vary. Whilst small in comparison to expected solar power, a wind power is provides additional insurance against cloudy dayes.

5.4 System Design

The time required to accomplish the 100km (+40% margin), 100 sample is broken down into that spent driving, doing science measurements and in low power/charging mode. The first two are calculated from Nomad's design speed and model of the science payload. The last by balancing the energy required for the former two by the net energy generated in charge mode.

Table 3 summarizes the mission time breakdown for Nomad as currently configured, and with proposed modifications for the mission. These times assume an average of 17W and 343W wind and solar power respectively. They are lower bounds, since they do not take wasted energy production (when batteries are fully charged) into account. The effects of this depends on battery capacity, weather variations and the mission planner. Work is in progress to model them using [LORAX autonomy reference]. Here we assume the 1 month time margin is sufficient to account for these as well as other unknown factors.

Table 3 Mission Time [days]

Mode	Current configuration		Mission Configuration	
Charge/Sleep	73	82%	0	0%
Driving	4.6	5%	4.6	28%
Science	12	13%	12	72%
TOTAL	89		16	

The current configuration requires 89 days, of which 73 are spent charging the batteries only. This is well in excess of the 30 desired mission duration. Studied modifications to reduce this are upgrading the avionics and sensors, upgrading the drive motors and gears, active power management, thermal insulation and increased speed.

Table 4 breaks down the power consumption for Nomad's current and proposed mission configuration. Replacing the current computation & control (from 1997) with the set developed for the Zoe vehicle [ref] saves 150W. Replacing the current harmonic drive system with more efficient planetary gears and matched motors reduces locomotion power by 50% (for a 700kg rover, climbing a 1 degree slope covered by hard-pack snow). These reduced power needs directly lead to 50% drop in transmission losses (assumption is a 48V battery voltage with switcher power supplies to boost voltage to 160V for current motors. Matching the battery and motor voltages would save an additional 66W and 33W for the current and mission configurations respectively).

Table 4 Average power consumption when active

Component	Current configuration	Mission Configuration
Computation & Control	190 W	40 W
Sensors	85 W	65 W
Communications	20 W	40 W
Science	40 W	40 W
Locomotion	437 W	222 W
Power transmission	116 W	61 W
TOTAL	888 W	468 W

Active power management to switch off unneeded electronics is not implemented on the current Nomad. A PMAD unit to switch off motor controllers, navigation computers and sensors while the rover is not driving, and everything else except for interior rover heating during charging saves additional power (Table 5), without it total mission duration would be at least 22 days.

Table 5 Average power consumption (excluding heater power)

Mode	Current configuration	Mission Configuration
Charge/Sleep	325 W	30 W
Driving	848 W	428 W
Science	385 W	128 W

Mounting all power consuming electronics (except for external sensors and wheel motors) inside a single insulated chamber alongside thermally sensitive components (especially batteries and disk drives) reclaims waste heat for thermal control. The current Nomad avionics produce a minimum of 262W of waste heat that can heat the main electronics enclosure. With the improved avionics and locomotion system, the mission configuration produces at least 30W. Because of the power margin, the mission configuration can tolerate thermal losses of up to 250W (made up of at least 30W of waste heat plus additional input from heaters) without affecting the mission time. By comparison, the current configuration generates at least 262W of waste heat. However, thermal losses in excess of that dramatically increase mission duration. Losses in excess of 300W mean the mission cannot be completed at all (total average power consumption exceeds production in charge mode).

Finally, increasing rover speed to 1m/s for the mission configuration decreases total mission duration to 14 days (if power management is implemented).

6. CONCLUSIONS

LORAX is a compelling astrobiological investigation, with a mature and reliable robot with navigational autonomy able to handle month long duration 100km traverses.

This investigation shows that with a set of straightforward modifications: 1) modernizing avionics 2) replacing the locomotion drive system, 3) implementing power management, and 4) limiting thermal losses to 250W, it is feasible to run Nomad from clean and renewable solar and wind power. Increasing locomotion speed has an insignificant effect compared to the time required for sample measurements.

Currently, Nomad has been validated for Antarctic navigation, a prototype ice coring and sample handling system built, and the UV sensor is still under development.

Future planned work will be to replace Nomad's generator with a solar/wind power system and verify their performance in the field, followed by the power saving modifications in time for the final 100km traverse.

Desired battery capacity is a key variable not addressed in this study. The companion paper [15] on the LORAX autonomy system shows how this will be studied.

Calculations show that if thermal losses are further reduced to 150W (and batteries suffiently large), Nomad is capable of doing a 1000km (+ 40% margin), 100 sample traverse in 2 months. This is just shy of reaching the South Pole from McMurdo station on the north coast. A further decrease in thermal losses to 100W (using more insulation and high heat capacity materials in the electronics box), and modest increases in the wind and solar power reduce this to 40 days, making feasible a traverse from the coast to the pole.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] Abyzov SS, Mitskevich IN, Poglazova MN, Barkov NI, Lipenkov VY, Bobin NE, Koudryashov BB, Pashkevich VM. (1998). Antarctic ice sheet as a model in search of life on other planets. ADVANCES IN SPACE RESEARCH 22 (3)363-368

[2] Abyzov, S. S., I. N. Mitskevich, et al. (1998). "Microflora of the deep glacier horizons of Central Antarctica." Microbiology 67(4): 451-458.

[3] Carpenter, E. J., S. J. Lin, et al. (2000). "Bacterial activity in South Pole snow." Applied and Environmental Microbiology 66(10): 4514.

[4] Poglazova MN, Mitskevich IN, Abyzov SS, Ivanov MV. 2001. Microbiological characterization of the accreted ice of subglacial Lake Vostok, Antarctica. MICROBIOLOGY 70 (6): 723-730

[5] Price P.B., and T. Sowers, "Temperature dependence of metabolic rates for microbial growth, maintenance, and survival", in PNAS 101, 4631-4636, 2004

[6] Price PB. 2000. "A habitat for psychrophiles in deep Antarctic ice.," in PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA 97 (3): 1247-1251

[7] Murarka, M., A. D.P. Miller, T. Taber & T. Hunt, "An Automated Sample Acquisition & Preparation System for LORAX," in *iSAIRAS 2005*, Munich, Germanany, September 2005

[8] Apostolopoulos, D., M.D. Wagner, B.N. Shamah, L. Pedersen, K. Shillcutt, W.L. Whittaker, "Technology and Field Demonstration of Robotic Search for Antarctic Meteorites" in International Journal of Robotic Research, special Field & Service Robotics issue, November 2000.

[9] Pedersen, L., M. Wagner, D. Apostolopoulos, and W.L. Whittaker, "Autonomous Robotic Meteorite Identification in Antarctica", in IEEE International Conference on Robotics and Automation 2001, Seoul, Korea, 2001

[10] Wettergreen, D., et. al., "Developing Nomad for Robotic Exploration of the Atacama Desert," *Robotics and Autonomous Systems*, Elsevier, Amsterdam, Netherlands, vol. 26, no. 2-3, February 1999.

[11] Vandapel, N., et. al., "Preliminary Results on the use of Stereo, Color Cameras and Laser Sensors in Antarctica," in *International Symposium on Experimental Robotics*, March, 1999

[12] Wettergreen, D., et. al. "Second Experiment in the Robotic Investigation of Life in the Atacama Desert of Chile," iSAIRAS, Munich, Germany, September 2005.

[13] Lambert, Tom, "How HOMER Calculates the PV Array Power Output," at http://www.nrel.homer/. Last modified: November 5, 2004.

[14] http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?na#s03

[15] Jónsson, A., C. McGann, L. Pedersen, M. Iatauro, S. Rajagopalan, "Autonomy Software Architecture for Lorax," in *ISAIRAS* 2005, Munich, Gernany, September 2005.