

SUN-SYNCHRONOUS NAVIGATION: TERRESTRIAL DEMONSTRATION AND ITS FUTURE FOR PLANETARY EXPLORATION

Paul Tompkins, David Wettergreen, Tony Stentz, William Whittaker
The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA 15213-3890 USA

Abstract

Sun-synchronous navigation is a technique that involves tracking the sun while exploring terrain. It is accomplished by traveling opposite to planetary rotation and in synchrony with the sun to always remain in sunlight. At appropriate latitude and speed, solar-powered rovers can maintain continual exposure to solar radiation sufficient for sustained operation. We are prototyping a robot, named Hyperion, for solar-powered operation in polar environments and developing sun-cognizant navigation methods to enable rovers to dodge shadows, seek sun, and drive sun-synchronous routes. We plan to conduct field experiments in a planetary-analog setting in the Canadian arctic to verify the algorithms that combine reasoning about sunlight and power with autonomous navigation and to validate parameters that will allow sun-synchronous explorers to be scaled for other planetary bodies.

Introduction

Future missions will demand rovers capable of exploring canyons, valleys and polar regions in search of water, ice and for signs of life. In the coming decades, the trend will be to explore ever more difficult terrain where science data tends to be the richest. Robotic exploration is restricted by the availability of solar power and implications of thermal conditioning needed to survive extremes of mid-day sun and overnight hibernation. With constant solar energy and moderate temperatures, surface exploration missions could last for months or years.

Sun-synchronous navigation is a new mission concept for surface exploration. With the robotics technologies necessary to enable it, sun-synchronous navigation can provide the capability of persistent, in some cases perpetual presence to explore, dwell in, and develop resource-rich regions of planets and moons.

Sun-synchronous navigation is accomplished by traveling opposite to planetary rotation, navigating with the sun, to remain continually in sunlight. [] At appropriate latitude and speed, rovers can maintain continual exposure to solar radiation sufficient for sustained operation.[] In some cases, by lagging the night-to-day terminator by the appropriate amount and remaining in the transient region between nighttime cold and daytime hot, rovers could maintain moderate ambient temperatures. (Figure 1)

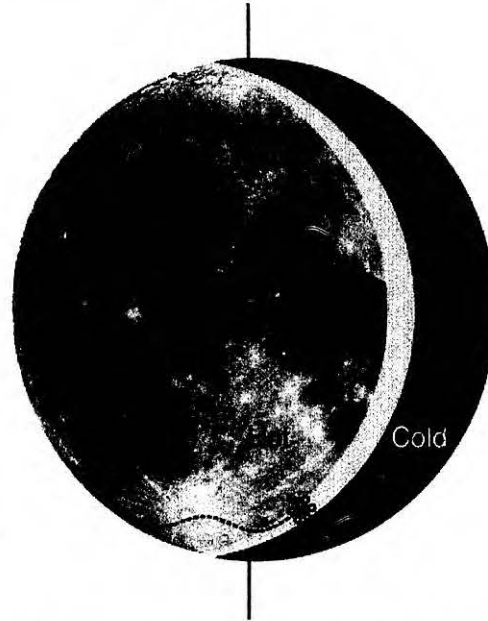


Figure 1 Navigating in synchrony with the sun in the lunar south polar region

Sun synchrony can be achieved through global circumnavigation when the speed of traverse is sufficient for the planetary rotation period, as at the equator of Mercury or the poles of the Moon. On bodies with axial inclination like the Earth and Mars, sun synchronous routes in polar latitudes follow a path of continuous exposure to the sun which circles above the horizon in summer.

We are prototyping a robot, named Hyperion, to exploit the advantages of sun-synchrony. Hyperion represents a class of polar rover notable for reduced mass, reduced complexity, and vertically-oriented solar panels. We are developing sun-cognizant navigation methods to enable rovers to dodge shadows, seek sun, and drive sun-synchronous routes. This requires planning capable of navigation in partially known, time-varying environments with additional consideration of power management. The rover must navigate around terrain features to avoid shadowing or seek locations of unobstructed sunlight to store power enroute.

We will conduct field experiments in a polar planetary-analog setting of the Canadian arctic during a period of continual direct sunlight. Our aim is to verify the algorithms for combining sun-seeking with autonomous navigation and to validate the parameters that will allow sun-synchronous explorers to be scaled for other planetary bodies. This paper

will motivate sun-synchronous navigation; describe the hardware and software of a solar-powered robot being developed at Carnegie Mellon; detail the planning algorithms to navigate sun-synchronous routes; and describe field experiments planned for July 2001.

Scenario

The moon's South Pole Aitken Basin is one potential target for rovers that motivates this research. Orbital missions over the past several years indicate a high probability of water ice trapped in permanently shadowed regions of the lunar poles, and hence present a strong scientific motivation for surface exploration. During summer months at the pole, the sun rises no higher than 1.5°, and appears to skim the complete horizon over the course of the moon's 29.5-day lunar month. Meanwhile, a combination of axial tilt and orbital eccentricity cause the Earth to inscribe a tilted elliptical path that rises to 6.7° above the horizon at its high point and falls to 6.7° below the horizon roughly two weeks later. The south pole region is known for its rough terrain; in conjunction with such low sun and Earth elevation angles, terrain causes substantial sun and communications shadowing. Surface shadow patterns change continually with the moon's rotation and progress of the Earth system about the sun.

A rover in this challenging environment would benefit from a mission planning capability that plans paths that maximize sun exposure and communications while satisfying operational constraints. Planning could discover paths that follow the course of sunlit regions to enable solar power and avoid extended exposure to the cold of lunar night. Such paths could also follow regions with direct line-of-sight to the Earth and relay spacecraft to allow high-rate imagery, teleoperated control and continual science data return. Additionally, mission objectives and limitations in a rover's ability to negotiate rough terrain might force the planner to deviate from these zones of relative safety. Entering a region of permanent dark to look for signs of water ice would force the rover to abandon sunlight and to enter low-lying areas where communications might be occluded by surrounding terrain. The mission planner should aid in timing this foray to maximize science data collection and rover contact while maintaining an adequate battery state-of-charge and maximizing the chance of survival. Similar strategies apply equally well to the canyon regions of Mars, where lighting and communications are severely limited by local topography.

Less extreme missions would also benefit from this form of integrated mission planning. For example, a planner could contribute to a near-term Mars rover mission by instructing a rover to terminate its daily activity schedule on a slope in a favorable orientation, thereby improving morning sun incidence on its solar array. Imaging of a particular

rock might be timed and placed to ensure direct sunlight and to avoid rover shadowing of the scene.

Applications

The concept of sun-synchrony is simple: follow the motion of the sun to remain exposed to sunlight. Continuous exposure to sunlight enables missions of exploration by solar-powered rovers that could last months or years.

Following the sun also enables rovers to follow a moderate temperature band in the region of transition from nighttime cold to daytime hot. On the Moon as well as Mercury and Mars this temperature band may allow rovers with minimal thermal protection to remain in Earth-like temperatures.

Table 1: Planetary Parameters []

	Mercury	Earth	Moon	Mars
Diameter (km)	4879	12756	3475	6794
Gravity (m/s ²)	3.7	9.8	1.6	3.7
Solar Irradiance (W/m ²)	9126.6	13681	1368	589.2*
Rotation Period (hours)	1407.6	23.9	655.7	24.6
Period of revolution (hours)	4222.6	24.0	708.7	24.7
Orbital Period (days)	88.0	365.2	27.3	687.0
Axial Tilt (degrees)	0.01	23.5	6.7	25.2
Mean Temperature (C)	167	15	-20	-65

At mid-latitudes sun-synchrony means traveling opposite to the rotation of the planet. On Earth, equatorial sun-synchrony is not feasible because of the high speeds required, and thus power. On Mercury the solar irradiance is 9 times greater than Earth (Table 2), gravity is one third and planetary rotation takes 176 Earth days. A rover circumnavigating Mercury's equator requires a small solar array and needs to travel only 4 kilometers per hour on average.

Table 2: Estimates of Sun-Synchronous Traverse of Equator, Pole, and Circuit

*Prior to atmospheric attenuation.

	Mercury	Earth	Moon	Mars	
Equatorial	Distance (km)	15327	40074	10914	21344
	Speed (km/hr)	3.6	1670	15	864
	Power (W)	87	45412	119	8930
	Solar Array Area (m ²)	0.04	227	0.4	75.8
Polar, 80°	Distance (km)	2662	6959	1895	3706
	Speed (km/hr)	0.6	290	3	150
	Power (W)	56	7927	62	1598
	Solar Array Area (m ²)	0.03	40	0.2	13.6
Circuit, 5km	Distance (km)	31	31	31	31
	Speed (km/hr)	0.01	1.3	0.04	1.3
	Power (W)	50.1	85	50.2	63
	Solar Array Area (m ²)	0.03	0.4	0.18	0.5

In Table 2 a number of possible traverse scenarios are considered. For each case the traverse distance, average speed, average power, and required solar array size are calculated. The required average speed is calculated from the traverse distance and the diurnal period of the Sun. The power required is an idealized calculation given by:

$$P = m_{rover}g_{vr\ soil} + 50W$$

The constant of 50 Watts is an assumed value that includes the constant power for all systems except the locomotion, for example computing and communication. For this comparison a rover mass of 100kg and soil resistance of 0.1 are assumed. The solar panel area is estimated with the following equation (with 20% efficiency):

$$A = \frac{P}{k_{efficiency}E_{irradiance}}$$

These simplified equations reveal the effects of gravity and speed on required power and highlight the scenarios under which sun-synchronous solar power may be feasible.

At high latitudes the rate of traverse decreases as the distance of circumnavigation decreases. On the Moon at 80° latitude a rover needs to travel at an average rate of 3 kilometers per hour to track the sun. The distance is long, 1895 km, but the high insolation (1368 W/m²), low gravity (1.6m/s²), and orbital period (27.3 days) combine for a viable solar-powered mission of polar circumnavigation.

A region of continual sunlight exists seasonally on planets with axial tilt. On Earth and Mars, at high latitudes, continuous direct sunlight occurs seasonally with duration dependent upon latitude. In this region, inside the arctic circles, a robot's solar panel must daily sweep 360° either through rotation or by following a spiraling path in order to

maintain sun-synchrony.

During the arctic summer of the Earth or Mars traverses by rovers with fixed, vertically-deployed solar arrays could circumnavigate a 5km radius feature with average speed of 1.3km/hr and solar panels of one half square meter or less. The possibility of a spiraling path that explores a spiraling path that explores a wide swath of the polar region is intriguing.

With a concurrence of features such as moderate temperatures, extended periods of sunlight [], and the possibility of *in situ* volatiles, polar regions of moons and planets offer excellent opportunities for long term missions. Sun-synchrony enables coverage of vast regions far from a landing site. This model of robotic operations allows diverse and detailed exploration that is not possible with traditional approaches. Sun-synchronous presence could pave the way for future space endeavors including scientific exploration, resource extraction, and human operations.

Sun-Synchronous Robot

We are prototyping a solar-powered robot to exploit the advantages and meet the challenges of sun-synchrony in polar environments. We have conceived a solar-powered vehicle physically capable of speeds of about 1/4 meter per second (1km/hr) in natural terrain.

The robot's name, Hyperion, is from Greek mythology and roughly translates to "he who follows the Sun" which is remarkably descriptive of what the robot is intended to do.



Figure 2 Hyperion solar-powered rover

Hyperion is 2 meters long and 2 meters wide and almost 3 meters tall with a near-vertically mounted solar panel of 3.5 square meters. (Figure 2) It carries this panel mounted upright to catch the low-angle sunlight of the polar regions. To support the panel its chassis is comparably sized.

It is fabricated of aluminum tubing and has four wheels on two axles. On the front axle an A-frame stands 1.5 meters high to support the stereo cameras and laser scanner at a proper height to see the surrounding terrain. All of Hyperion's computers, electronics and batteries are enclosed in a single sleek body mounted between the axles. Hyperion weighs 156 kilograms.

Hyperion is designed for operation on Earth but due to the relatively low insolation and low efficiency of commercial solar cells it must be efficient in terms of power consumption. Its steady state power consumption is 75W.

To drive straight without skidding Hyperion consumes about 60W on level terrain. This increases on slopes with 15° demanding 75W. If wheels skid with respect to each other power is spent in soil work. Careful tuning of the control will ensure that turning is smooth and skidding is minimized.

Sun-Synchronous Navigation

To operate sun-synchronously, Hyperion must optimize the orientation of its solar panel with respect to the sun. This imposes significant new constraints on the navigation problem. It's ability to navigate must go beyond avoiding obstacles and reaching goal locations to maintaining a preferred orientation while accomplishing this. Hyperion can run into difficulty not just from box canyons but improper orientation or just getting behind the clock. This calls for a control architecture that enables rigorous error detection and flexibility in the command structure to facilitate error recovery even including operator intervention.

The underlying control architecture exhibits a property of sliding autonomy in that an operator can choose various operational modes. The operator can interact with Hyperion by directly teleoperating its actions, by allowing Hyperion to safeguard operator actions or by allowing Hyperion to navigate autonomously. Hyperion, when it detects anomalous conditions will, after stopping motion, slide into a safeguarded mode and wait for guidance from an operator.

In the safeguarded teleoperation mode, the operator guides the robot with coordinated motion commands and receives state direct from the sensors, including onboard cameras. (Figure 3)

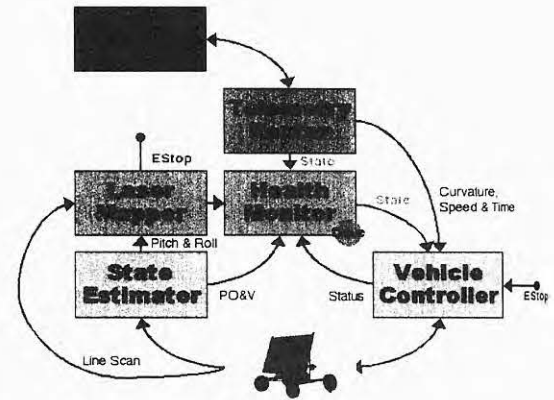


Figure 3 Safeguarded Teleoperation

A State Estimator integrates sensor information including position, orientation and speed. A Health Monitor evaluates state, safeguarding the robot. It commands an emergency stop if an anomalous condition occurs. The Laser Mapper detects near obstacles and signals the Health Monitor of imminent collision. With a total latency of 200msec the robot stops on obstacle section.

In its autonomous mode (Figure 4) a Stereo Mapper classifies terrain, generating a traversability map from stereo imagery at 5Hz. The Navigator evaluates the map and selects a path that best leads the robot to the next goal

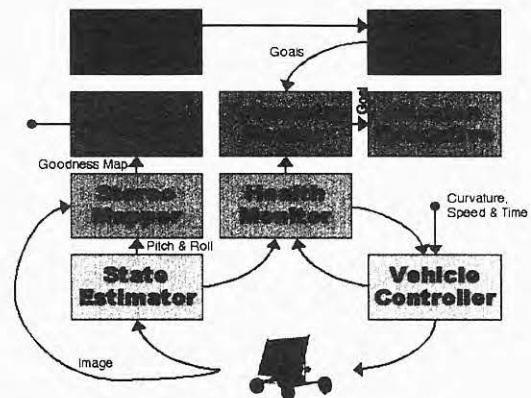


Figure 4 Navigational Autonomy

The Mission Planner determines sun-synchronous goals and commands them to the Mission Executive for execution. These goals, on a 25m resolution, drive the Navigator along a sun-synchronous route. If the local goal cannot be achieved or if the time to reach the goal jeopardizes sun-synchrony, the Mission Executive signals the Mission Planner to revise the route to accommodate problems in position or time.

Sun-Synchronous Mission Planner

The Mission Planner is called TEMPEST (Temporal Mission Planner for the Exploration of Shadowed Terrain). TEMPEST resides as a component of the upper, deliberative layer of an autonomous control architecture, but displays qualities that enable quick replanning that provides response to new data characteristic of reactive systems. It operates on mission objective specifications (e.g. science survey target locations, required durations at each site), planetary models (e.g. ephemerides, digital terrain models), and rover models (e.g. power requirements, energy collection, data and communications constraints) as a basis for analyzing the effects of path and activities on mission outcome (Figure 5).

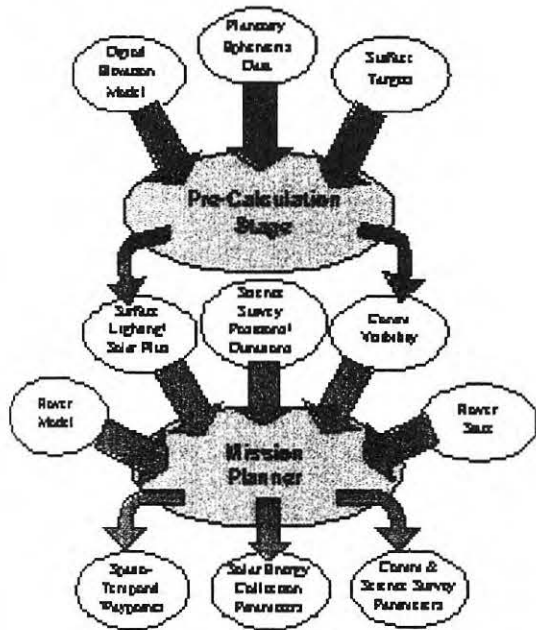


Figure 5 TEMPEST

The dynamic nature of the domain, deriving primarily from planetary and rover motion and their effects on lighting and communications, requires an approach that emphasizes time as a plan parameter. In its current instantiation, TEMPEST populates a spatio-temporal grid with terrain and line-of-sight data, and performs a search on the grid to determine a mission sequence that satisfies mission and operational constraints while optimizing a parameter (e.g. distance traveled). TEMPEST generates a plan consisting of path waypoints defined by spatial coordinates and times, and associates activities with waypoints along the traverse (e.g. orient the solar array to a particular attitude and charge the battery for 20 minutes). The resulting plan is then delivered to a middle, executive architecture layer for execution.

TEMPEST simultaneously derives a path plan and a framework for activity scheduling. Relevant events are considered in the context of the rover path, resulting in plans that are integrated from the outset. For example, the choice

of path impacts energy used for locomotion (through distance, speed and slope), when solar energy can be gathered (through shadowing and solar array orientation), and consequently defines when recharging must occur.

A salient feature of TEMPEST is its capability for fast replanning. The first search of the spatio-temporal grid is the most computationally intensive as it determines the optimal trajectory from any point to the goal. As new information is gathered, we employ an algorithm that propagates the changes in the grid efficiently to only those cells that can affect subsequent search outcomes. The result is that replanning can be done on the fly as the rover travels between waypoints in the previous plan.

TEMPEST combines planetary models with models of rover performance and operational constraints to form a basis for path and time search. TEMPEST utilizes digital elevation data sets to encode terrain in the area of operations, and pre-calculates slope and aspect using this data. Digital elevation models are becoming more readily available on a global scale and at ever-increasing resolution for both Mars [] and the moon [,]. It is expected that long-distance surface investigations would be preceded by detailed orbital surveys from which digital elevation data could be derived, as in [].

Surface lighting, communications visibility and surface-to-surface visibility are all fundamentally determined by line-of-sight geometry. TEMPEST employs a ray-tracing algorithm to determine line-of-sight visibility from the sun to cells for lighting and shadows, from the Earth to cells for communications and cell-to-cell to determine visibility from the rover to surrounding terrain. Elevation and slope data are de-projected from maps to the planetary sphere or ellipsoid to account for horizon effects. Planetary motion is modeled using JPL CSPICE software Error! Reference source not found. For line-of-sight data that are time dependent (e.g. sunlight), the software pre-calculates exposure for the complete map for each time slice. The result essentially amounts to a movie encoding the angle of incidence of the source on the terrain for each time step. In addition to calculating line-of-sight, TEMPEST uses a simplified model to calculate available solar flux to account for solar distance and gross atmospheric effects, if applicable.

TEMPEST models the power load generated during rover operations and solar power production. A simple model of locomotion power as a function of speed and slope combines with steady-state electronics power loads for the overall rover power load. Solar power generation depends on sun angle of incidence on solar arrays, panel area and cell efficiency. The model allows for body-fixed or gimballed arrays, and takes the effect of slope and rover pose into account when calculating panel sun angles. Though currently not addressed, future versions may employ communications models to estimate signal strength or available data rate.

TEMPEST finds shortest paths that are constrained

by the available sunlight and the energy capacity of the rover's battery. The planner represents and reasons about two spatial dimensions, time, and energy level. To manage the high dimensionality of this space, TEMPEST uses the Incremental Search Engine (ISE) [1]. Like D*, ISE is a heuristic search algorithm that incrementally re-plans optimal paths, but ISE also efficiently manages constraints on the feasible set of solutions. ISE plans an initial path given all known information about the world that satisfies the constraints and is optimal. As the vehicle follows the path generated by ISE, it discovers new information with its sensors. ISE stores this new information and re-plans a new path, in real time, that is both feasible and optimal. This process repeats until the vehicle reaches the goal or determines that it cannot.

ISE uses incremental graph theory techniques to repair both the feasible set of solutions and the optimal path within it. The algorithm is time efficient because it determines which portions of the search space are affected by the new information and limits the re-computation to those portions. The algorithm is space efficient through the use of three mechanisms:

- **Dynamic state generation:** ISE creates a state when it is needed and deletes it when it no longer serves a purpose; this feature precludes the need to allocate an entire multi-dimensional space even though only a small part of it may be searched.
- **State dominance:** ISE determines when one state dominates another and prunes the dominated state to minimize unnecessary state proliferation.
- **Resolution pruning:** ISE reasons about parameter resolution and prunes the lesser states from a resolution-equivalent class. This feature can dramatically reduce the number of states while still preserving resolution optimality.

ISE is the only real-time, optimal re-planner that provides these mechanisms for managing high-dimensional, constrained problems. Examples of search problems that ISE can solve include finding the shortest path that arrives at the goal at or before time T; finding the safest path with no more than 10 minutes of lost radio contact; and finding the path that maximizes visibility of interesting areas without exhausting the vehicle's fuel supply. ISE can solve these problems even when the cost and constraint information changes during the course of the traverse.

Figure 6 shows several steps of a sun-synchronous path generated by TEMPEST from the start position in the upper left to the final goal in the lower right.

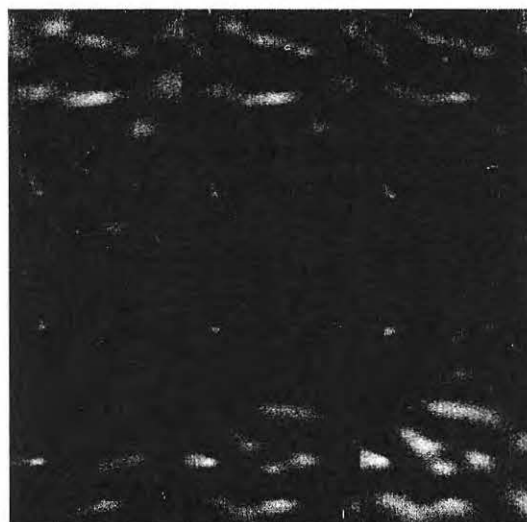


Figure 6 Sun-synchronous route plan (left to right, top to bottom) shows changing shadows with changing position of the sun

As the sun moves the shadows on the terrain change. The mission planner maintains its power level sufficient to traverse the terrain even when it must turn away from the sun. By fully charging its reserves the planner finds that it can across a shadowed region to reach an intermediate waypoint. In this manner, through a series of waypoints Hyperion can track a complete sun-synchronous circuit.

Polar Field Experiment

We intend a field experiment in a polar planetary-analog setting in a location of continual direct sunlight. Our aim is to verify the algorithms for combining sun-seeking with autonomous navigation and to validate the parameters that will allow sun-synchronous explorers to be scaled for other planetary bodies. For a particular rover, measurements of locomotion power in various terrains must be verified empirically. For a particular implementation of the navigation software, the ability to maintain preferred orientation while avoiding local obstacles and reaching global goals, must be characterized and quantified. Experimental verification and measurement is an important part of determining the validity of sun-synchronous navigation.

We plan initial field experiments with the Hyperion rover in July 2001 on Devon Island in the Canadian high arctic. The area is particularly notable for the lunar-like breccia inside Houghton Crater and Mars-like "planitia" to the northwest of the crater. We conduct experiments in these terrains to characterize Hyperion's performance on Earth and to study potential performance beyond Earth.

At 76°N, this area has 24 hours of sunlight with insolation ranging from lows of 250W/m² to highs of 800W/

m². The key limitation to a terrestrial traverse is the low amount of available insolation. For a continuous 24 hr traverse the problem is the gap between the maximum and minimum power generated each day. A clear understanding of the variable relationship between environment and the robot is needed for evaluating sun-synchronous routes and enabling sun-synchronous exploration.

Conclusion

The great explorers of history went beyond their own backyard, to follow rivers, cross mountain ranges, reach the poles, and circumnavigate the globe. The ambition then and now is to discover the unknown: to explore regions, not just sites; to analyze, not just observe; and to operate effectively and reliably without excessive support. Robotic explorers capable of sustained operation will perform rigorous in situ science, detailed surveys, resource characterization, and exploration on a vast scale.

This paper has described the concept of sun-synchronous navigation and provides a preliminary report on progress towards sun-synchronous navigation with a new solar-power robot and planning and control system Design refinements and component tests are currently underway with field experimentation anticipated in July.

Acknowledgements

This paper describes the work of the Sun-synchronous Navigation project and all of its members are important contributors. We acknowledge and thank Dimi Apostolopoulos, Jesse Boley, Bernardine Dias, Stewart Morehead, Ben Shamah, Reid Simmons, Sanjiv Singh, Surya Singh, Jim Teza, Chris Urmson, Vandi Verma, Mike Wagner, and David Wilkinson. Field experimentation will be conducted in collaboration with the NASA/SETI Haughton-Mars project, Pascal Lee, Principle Investigator. This work is supported by NASA under grant NAG9-1256.

References

- [1] C. Acton, "Ancillary Data Services of NASA's Navigation and Ancillary Information Facility," *Planetary and Space Science*, vol. 44, no. 1, pp. 65-70, 1996.
- [2] D. B. J. Bussey, M. S. Robinson, P. D. Spudis, "Illumination Conditions at the Lunar Poles," in *Lunar and Planetary Science 30*, abstract #1731, Lunar and Planetary Institute, Houston, TX, March 1999.
- [3] A. Cook, P. D. Spudis, M. S. Robinson, T. R. Watters, and D. B. J. Bussey, "The Topography of the Lunar Poles from Digital Stereo Analysis", *Proceedings of the 30th Lunar and Planetary Science Conference*, Houston, CDROM abstract #1154, 1999.
- [4] R. Li, F. Ma, F. Xu, L. Matthies, C. Olson, and Y. Xiong, "Large Scale Mars Mapping and Rover

Localization Using Descent and Rover Imagery", *Proceedings of ISPRS 19th Congress*, Amsterdam, July 2000.

- [5] J. L. Margot, D. B. Campbell, R. F. Jurgens, M. A. Slade, "Digital Elevation Models of the Moon from Earth- Based Radar Interferometry", *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 38, No. 2, March 2000.
- [6] National Space Science Data Center, Planetary Fact Sheet, <http://nssdc.gsfc.nasa.gov/planetary/factsheet>
- [7] K. Shillcut, "Solar Based Navigation for Robotic Explorers," Ph.D. thesis, CMU-RI-TR-00-25, October 2000.
- [8] D. Shrounk, "Sun-Synchronous Operation", Workshop Discussion, ISE Lunar Conference, 1995.
- [9] D. E. Smith, M. T. Zuber, S. C. Solomon, R. J. Phillips, J. W. Head, J. B. Garvin, W. B. Banerdt, D. O. Muhleman, G. H. Pettengill, G. A. Neumann, F. G. Lemoine, J. B. Abshire, A. B. Ivanov, P. J. McGovern, H. J. Zwally, T. C. Duxbury, "The Global Topography of Mars and Implications for Surface Evolution", *Science*, Vol. 284, May 28, 1999. Whittaker, W., Kantor, G., Shamah. B., Wettergreen, D., "Sun-Synchronous Planetary Exploration," AIAA, 2000.
- [10] A. Stentz, "Optimal Incremental Search for High-Dimensional, Constrained Path Finding Problems," Carnegie Mellon Robotics Institute Technical Report CMU-RI-TR-???, 2001.