Robotic Planetary Exploration by Sun-Synchronous Navigation

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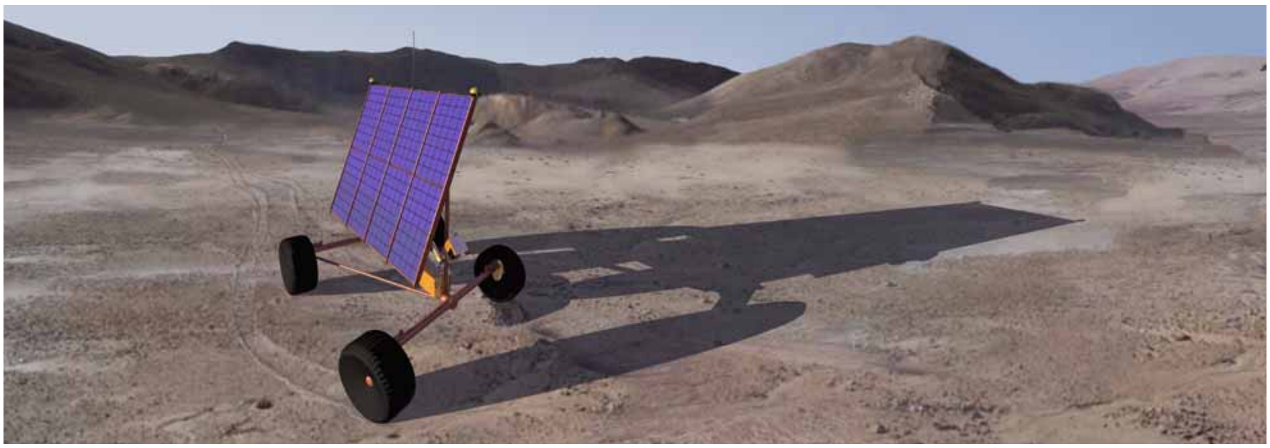

Figure 1 Concept illustration of a sun-synchronous rover for polar exploration

Keywords: planetary surface exploration, Hyperion solar-power mobile robot, sun-synchronous navigation

Abstract

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, solar-powered rovers can maintain continual exposure to solar radiation sufficient for sustained operation. We are prototyping a robot, named Hyperion, (Figure 1) 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. The paper provides a preliminary report on progress towards sun-synchronous navigation.

1 Introduction

Robotic exploration of planetary surfaces is restricted by the availability of solar power and implications of thermal conditioning needed to survive extremes of midday sun and overnight hibernation. With constant solar energy and moderate temperatures, surface exploration missions could last for months or years.

We advocate sun-synchronous navigation as a 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. [6] At appropriate latitude and speed, rovers can maintain continual exposure to solar radiation sufficient for sustained operation.[8] In some cases, by lagging the night-to-day terminator by the appropriate amount and seeking the transient region between nighttime cold and daytime hot, rovers could maintain moderate ambient temperatures. (Figure 2)

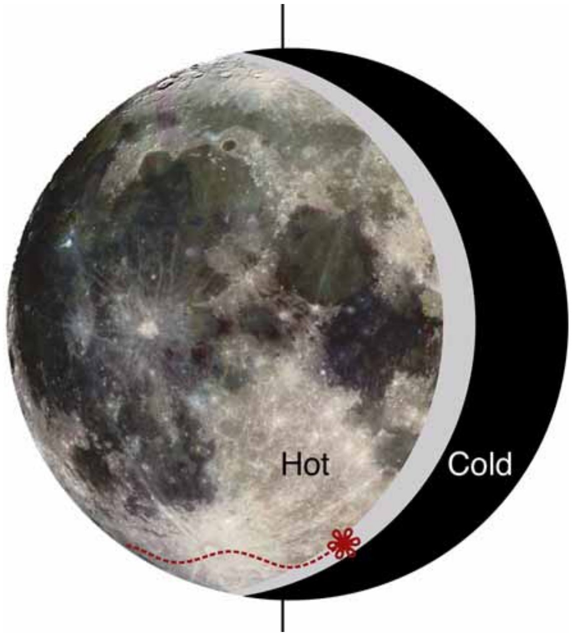

Figure 2 Navigating in synchrony with the sun in the lunar south polar region

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.

At Carnegie Mellon 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 describe the concept of sun-synchronous navigation and its importance; 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.

2 Sun-Synchrony

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.

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 1), 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 1: Planetary Parameters [4]

	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	1000	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

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

		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° latitude	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 radius	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 in (1). The constant of 50 Watts is an

$$P = m_{rover} g v r_{soil} + 50W \tag{1}$$

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 (2) and an assumed efficiency of 20%. These simplified equations reveal

$$A = \frac{P}{k_{efficiency} E_{irradiance}} \tag{2}$$

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/m^2), low gravity (1.6m/s^2), 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 possibly of a spiralling 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 [2], 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.

3 Solar-Powered Polar Rover

Although the concept of sun-synchrony is simple and appealing, accomplishing it may be difficult. The first challenge is to design a robot that is capable of traversing rough, natural terrain at sufficient speed while remaining energy efficient enough to be solar powered. The lower the mass of the robot, the smaller the solar panel it needs to drive itself.

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 1/2 meter per second (2km/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.

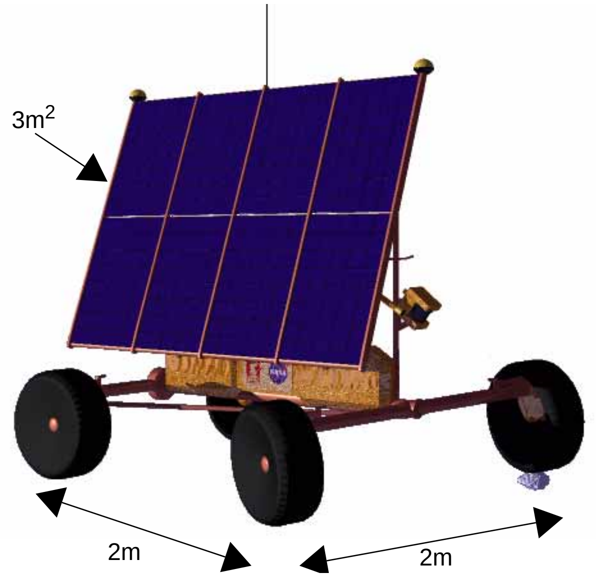

Figure 3 Hyperion solar-powered rover

Hyperion is 2 meters long and 2 meters wide and almost 3 meters tall with a vertically mounted solar panel of over 3 square meters. (Figure 3) It carries this panel mounted vertically to catch the low-angle sunlight of the polar regions. (Figure 4) To support the


Figure 4 Hyperion solar-panel assembly

panel its chassis is comparably sized. The frame is composed of thin-wall aluminum tubing with subassemblies clamping to the frame structure. Each wheel has an individual drive motor for maximum locomotive performance and steering is performed by the rotation of the rigid front axle. On the front axle an A-frame stands about 1.5 meters above ground level to hold 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 body mounted between the axles. In total, Hyperion weighs close to 140 kilogram.

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, as detailed in Table 3 is 75W.

Table 3: Steady-state Power Requirements

Subsystem	Watts
Computing	40
Communication	6
Sensing	29
Total	75

To drive straight without skidding Hyperion consumes about 60W on level terrain. (Table 4) 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.

Table 4: Locomotion Power Draw Estimates

Action (at 1 km/hr)	Torque (Nm)	Power (W)
Drive straight	17	60
Climb15° slope	23	75
Skid steer		150
Dead lift	83	290

4 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. (Figure 5) Hyperion, when it detects anomalous conditions will, after stopping motion, slide into a safeguarded mode and wait for guidance from an operator

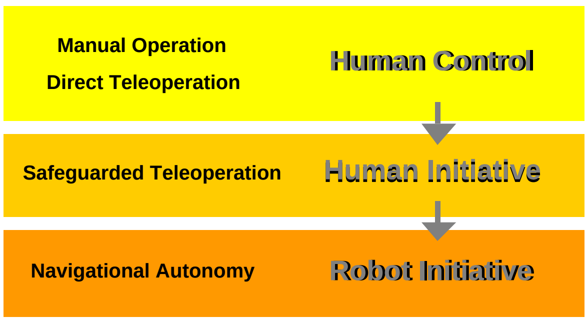

Figure 5 Operational Modes

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 6) 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.

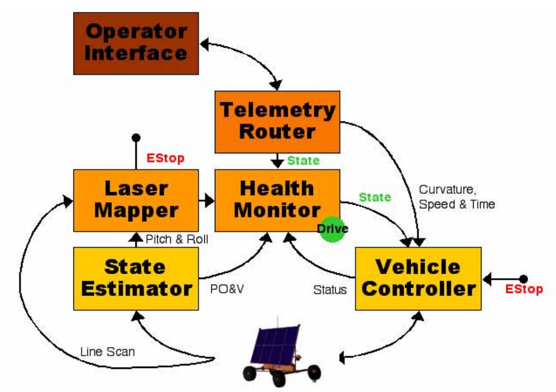

Figure 6 Safeguarded Teleoperation

In its autonomous mode (Figure 7) 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

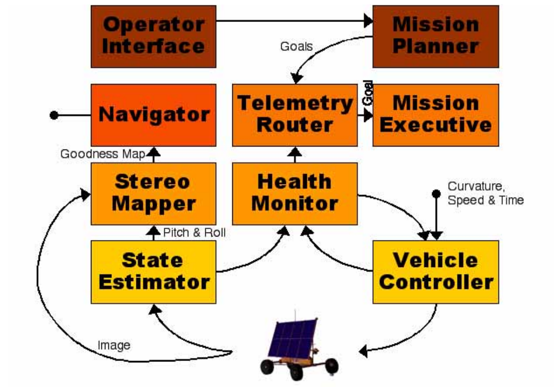

Figure 7 Navigational Autonomy

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.

Figure 8 show the modules active during each of the operational modes.

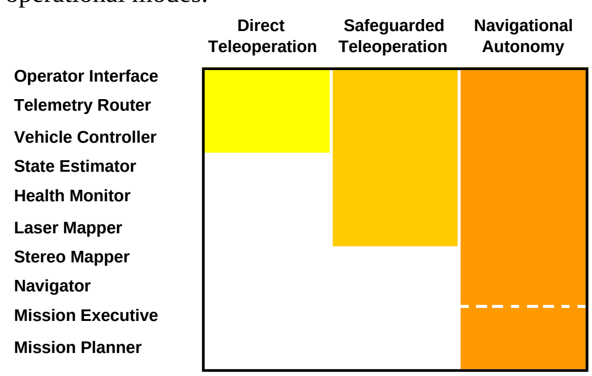

Figure 8 Modules active versus operational modes

We are developing sun-cognizant spatial and temporal planning software for rovers to dodge shadows, seek sun, and drive sun-synchronous routes. This requires planning capable of autonomous navigation in partially known, time-varying environments with additional considerations of power and thermal management.

To navigate sun-synchronously Hyperion must have a map of the terrain, an estimate of where it is located, and the current time. Digital elevation maps at 100m resolution or better are available for most of the Earth and that resolution or better is or will soon be available for interesting areas of the Moon and Mars. To determine its position and orientation Hyperion carries a pair of GPS receivers and odometric sensors. Hyperion computes the position of the individual antenna and then determines its orientation from the known, relative position of the individual antenna positions. Hyperion's State Estimator also incorporates odometric sensing on its wheels so that it can estimate its motion by integrating information. This is important beyond the Earth where GPS is not available and odometry combined with star, sun, or terrain landmark tracking would form the basis of estimating position and orientation.

The motion of the sun at a particular location combined with terrain elevation models indicate whether the sun is visible at a given location, and at which angle the sunlight will be incident on solar panels. The geometry given by ephemeris [1] is used to generate the sunlight model as a function of surface topography. Rover terramechanical models are used to predict the power consumption of a rover traversing the landscape. Together with models of lighting, estimates of the ratio of available power (sunlight) to required power are generated.

Figure 9 shows several steps of a sun-synchronous path generated by the Mission Planner from the start position in the upper left to the final goal in the lower right. As the sun moves the shadows on the terrain

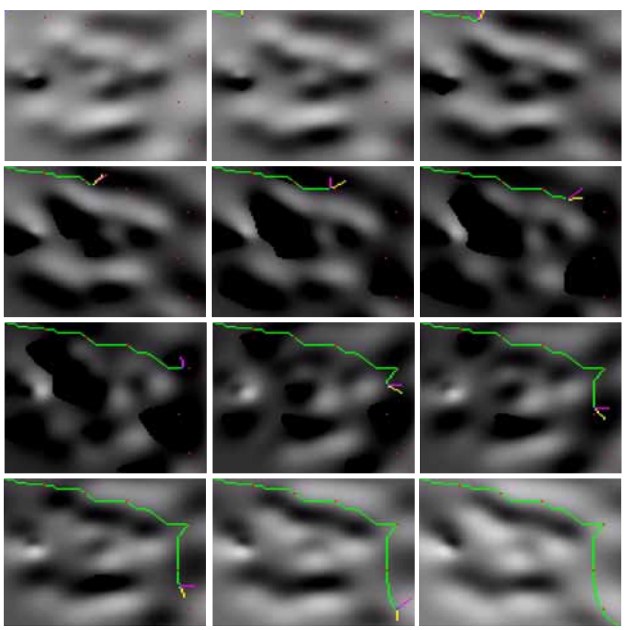

Figure 9 Sun-synchronous route plan (left to right, top to bottom) shows changing shadows with changing position of the sun

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.

5 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 will conduct 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 Haughton Crater and Mars-like planitia to the northwest of the crater. (Figure 12) 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/m^2 to highs of 800W/m^2. The key limitation to a terrestrial traverse is the low amount of available insolation. Figure 10 shows the predicted power from a pointed 3m^2 solar panel for a 76° latitude. For a continuous 24 hr traverse

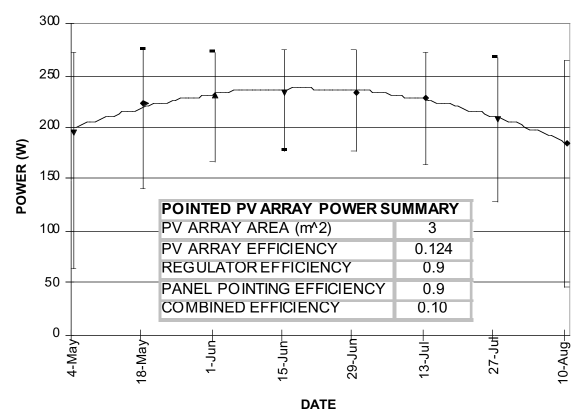

Figure 10 Predicted power output (W) versus date for a 3m^2 pointed panel at 76°N

the problem is the gap between the maximum and min-

Figure 12 Panoramic view of terrain on Devon Island, Canada

imum 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.

Using a high resolution digital elevation map, and a desired radius the rover will autonomously plan and then execute a sun-synchronous circuit that is integrated to the terrain, as in. The path must avoid shadows of local features while keeping up with the sun as it clocks around the center point of the traverse.

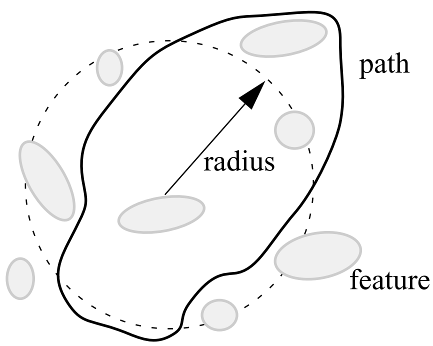

Figure 11 Sun-synchronous circuit conforming to local terrain features

6 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

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