SOLAR POWER EXPERT FOR REMOTE ROBOTIC EXPLORERS

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ABSTRACT

Robotic exploration of remote areas to assist or replace human exploration reduces the cost, hazard and tedium of such exploration. For remote explorers, power is the most critical resource, and the most common source of that power is solar energy. Information about the robot configuration, the planned path, the terrain and the position of the sun can be processed by a solar power expert software module to calculate the power provided by a given plan of action. Using this information to select the best plans will enable remote robotic explorers to extend their lifetimes. This paper presents the development of a solar power expert and its implementation on a simulator. Several patterned path plans are evaluated with various solar panel configurations, starting times and locations, concentrating on polar regions.

1. EXPLORATION ROBOTS

Capable and adaptable robots are needed for exploring areas too dangerous or costly for humans to visit. Planets, moons, and remote earthly locations such as polar regions and volcanic craters are some such areas. The absence of close human presence in these places requires some degree of autonomy, particularly when the work area is dynamically changing and not fully known ahead of time. Preprogramming the robot is not an option when insufficient information is available. Teleoperation in remote areas causes multiple difficulties: time delays prevent rapid reactions to dangerous situations and lengthen multi-stage tasks unacceptably, while limited sensor information frustrates human interpretations and reactions. Autonomous operation allows robots to reason about their ability to perform various tasks as well as the probable results of performing those tasks, all with respect to the current, possibly changing environment.

To succeed in their mission of exploration, much work needs to be extracted out of few resources. The financial budget for robotic explorers is always limited, creating size and weight restrictions for any robot destined to be launched into space or placed into other remote areas. Thus, efficient use of resources can be of vital importance to robotic explorers, making the difference between success and failure of the mission.

The most critical exploration resource is power, and optimizing its generation is crucial. For this class of remote, outdoor, exploring robots, solar power is the mode of choice [Colozza]. The use of non-renewable batteries or fuel cells alone is not feasible for extended missions, due to the enormous weight and volume that would be needed to transport the required amount. Nuclear power is another option, but one which requires extensive safety reviews, and public and governmental approval which may take years to complete. Despite drawbacks of solar power such as inefficiencies due to material composition, dust storms or clouds, solar power is a prime power source in the inner solar system, ranging from the Sun to Mars.

To generate solar power for use by a mobile robot, several factors need to be considered. Solar power generation depends not only on the static solar panel configuration, but also on the changing orientation of those panels with respect to the sun, and the current visibility and strength of the sunlight reaching the panels. The motion of the sun over time combined with local terrain maps will indicate whether or not the sun will be visible at a given location, and at which angle the sunlight will be incident on the panels. A solar power "expert" can simulate these environmental factors while evaluating a given plan of action, combining the software simulation with the robot configuration to estimate the amount of solar power that will be generated while enacting that plan. This estimate can then be used by the robot to determine which plan to choose and what actions to perform.

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2. EXPLORATION MODES

For robotic explorers, extensive travel through a region is a primary task, often accomplished using complete coverage patterns. Such patterns enable the robot to pass over every portion of the area, either physically or with its sensors. Coverage of an area is a common theme in several earthly applications, whether pursued robotically or by humans, such as landmine detection and meteorite searches. Understanding the application aids in determining the best way to cover the area.

The application for which this work was performed is a robotic Antarctic meteorite search. Antarctica is one of the most remote locations on Earth. Its cold and pristine environment makes it one of the best places to find meteorites. Wind scours off the top layers of ice flows blocked by mountains or other obstructions, revealing concentrations of meteorites [Cassidy]. The extreme conditions also make it difficult for humans to work there, but a robot designed to explore this area can provide great scientific returns.

A primary characteristic of this application which affects the mission profile is the polar location. The same consequences discussed here are equally relevant to polar locations on the Moon and other planets. While planetary and lunar surface missions to date have been near-equatorial expeditions, polar regions are increasingly of interest to researchers. For example, searching for frozen volatiles such as water ice on the lunar south pole is currently under investigation [Deans], and the Mars Polar Lander will land near 75° south latitude on Mars later this year.

Solar power generation near the equator is simplified, but in the polar regions, the sun remains low on the horizon, producing long shadows and enhancing the effect of terrain features. Calculating the location and movement of shadows is thus complicated, but necessary to ensure adequate generation of solar power. In some cases, long periods without sunlight may occur, at which time dependence on other power sources or hibernation must occur.

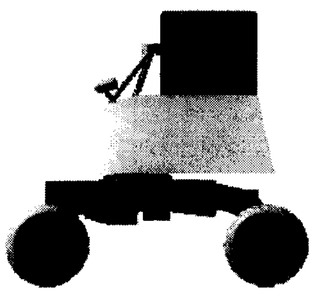

FIG. 1: Vertical Solar Panels on Robot

Due to the low sun angles, solar panels must be more vertical than horizontal to gain the most power. When movable panels are not possible or desirable, choosing the best orientation for the solar panels is vital. One configuration considered for the meteorite searching robot is pair of vertical panels back to back, placed along the spine of the robot (see Figure 1).

3. SOLAR POWER EXPERT

The first step in calculating the amount of power which can be generated by an exploring robot is determining its position throughout a plan of action. A simulator was designed which takes a desired coverage pattern and updates the position of the robot every second as it follows the pattern. Two basic types of coverage patterns have been implemented so far: a straight rows pattern, and a spiral pattern, as shown in Figure 2.

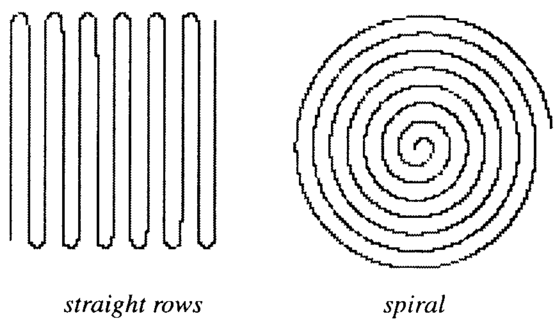

FIG. 2: Coverage Pattern Types

Each pattern is defined by a module which determines the steering angle with which the robot should drive to continue the pattern. By knowing the current location of the robot, such as with differential GPS, and knowing certain parameters of the pattern, such as starting and end points and row lengths, the pattern modules can correct for deviations from the pattern and bring the robot back on track.

The second step is to determine the position of the sun relative to the robot's current location. The current basis of the solar power expert is a function from the SatTrack program [Bester] which calculates the right ascension, declination and distance of the sun and moon from the Earth's center for a given Julian date. The results from this function are transformed to give the altitude and azimuth of the sun as seen from a given location on the Earth's or moon's surface for a given date and time.

Terrain features are then taken into account. By comparing the surrounding terrain elevations in the direction of the sun from the robot, any occlusions of the sunlight can be determined (see Figure 3). Two levels of shadow finding are proposed, based on high and low resolution terrain maps. A small, high resolution area can be processed quickly to determine if any local obstacles are blocking the light. This terrain map will be generated in realtime, as the robot explores its surroundings with various sensors and adds new obstacles and elevation information to its database. The second level of shadow finding is based on a lower resolution map of the area containing information gained beforehand from remote sensing or digital elevation maps. This type of map can provide information about large areas of shadow which can be used in planning where to start exploring first.

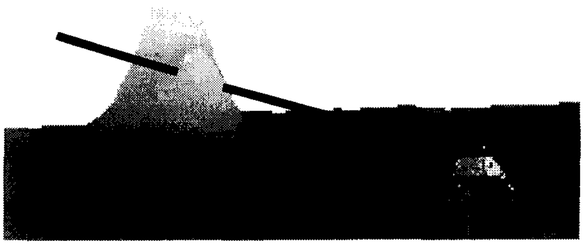

FIG. 3: Determining Terrain Occlusions of Sun

Finally, the robot's pose and solar panel configuration are used to determine the amount of solar power which can be generated. The normals to the robot's solar panels are defined by the configuration. The robot's roll, pitch and yaw are then used to calculate the current direction in which those normals point relative to the angle of sunlight. The power generated varies with the cosine of that relative angle, decreasing as the angle increases.

The power generation calculation is performed at each step of the way along the coverage pattern. Recalculating every second provides an accurate enough evaluation considering the speed of the robot and the speed of the sun's movement across the sky. Both the instantaneous power produced over time and the total energy generated for the pattern can be calculated and used to compare different coverage patterns.

4. SIMULATION RESULTS

Two types of tests were performed with the solar power expert. For the first type of test, the two different coverage patterns, straight rows and spiral, were evaluated for six different latitudes on Earth's surface, at three times of year for each latitude. The time of day was chosen such that the sun was near its peak elevation at that time. The starting heading of the robot was chosen such that the vertical solar panels were perpendicular to the angle of sunlight, producing the greatest amount of power at that time. In addition to the back-to-back vertical solar panel configuration, an additional configuration of a single solar panel placed horizontally on top of the robot was considered, to provide more information for the lower latitude test cases. All three solar panels were assumed to be 1 meter square in size, producing a maximum power output of 100 Watts.

The strength of sunlight reaching the robot can differ greatly depending on the sun's elevation above the horizon, due to diffraction effects. While this difference was not accounted for in the energy sums, the main values considered were the ratios of total energy for the different patterns and different solar panel configurations. Since both patterns are performed with the same sun angles, for both configurations, the sunlight strength cancels out.

The pattern simulations were based on rows or spirals 8 meters apart, on flat ground. The straight rows pattern used rows 100 meters long, and a total width of 100 meters. At a speed of 0.15 m/s, this pattern requires approximately 2 hours and 40 minutes. The spiral pattern was performed for the same amount of time. Table 1, at the end of this paper, shows the results of the simulations. A longitude of 0 W was used for all simulations. For southern latitudes, January 1st, 2000 was used for summer, October 1, 1999 for spring, and July 1, 2000 for winter. For northern latitudes, January 1, 2000 was used for winter, October 1, 1999 for fall, and July 1, 2000 for summer.

While the purpose of the solar power expert is to evaluate possible plans of action during the mission for the current terrain and area, the evaluations of these test cases show some basic trends which might lead to heuristics for simplifying the online planning, as well as aid in determining the best solar panel configuration to use for the designated location. For example, the side solar panels are preferable for higher latitudes and during seasons with lower sun angles, as expected. For intermediate locations, simulations can quantitatively predict which configuration is best.

For the side solar panel configuration, the differences in power generation between the two patterns are greater during the winter than the summer, for all latitudes. Generally, the differences are also greater for higher latitudes, during the same season. The commonality between these trends is lower sun angles, implying that power generation is more sensitive to the type of pattern when the sun angle is low. For the top solar panel configuration, both patterns produce the same power, as the robot's orientation is irrelevant.

In all cases except the summer at 40 N latitude, the straight rows pattern generates more power than the spiral pattern. Of course, this depends on the initial heading of the straight row with respect to the sun. When evaluating plans for a specific time and location, the solar power expert can calculate just how much better a given coverage pattern is and in which direction to start.

The second type of test concerns the effect of terrain on sun visibility for three different latitudes on Earth. For the terrain map, a digital elevation map of the moon's Tycho crater [Margot] was modified by reducing the vertical scale by a factor of 100, reducing the horizontal scale by a factor of 1000, and "placing" the crater region at several locations on Earth, to generate graphs which clearly demonstrate the effect of latitude on terrain shadowing. The straight rows coverage pattern used is superimposed on the crater region in Figure 4. The pattern is 100 meters by 80 meters, with rows 8 meters apart. The simulated robot traveled at 0.15 m/s.

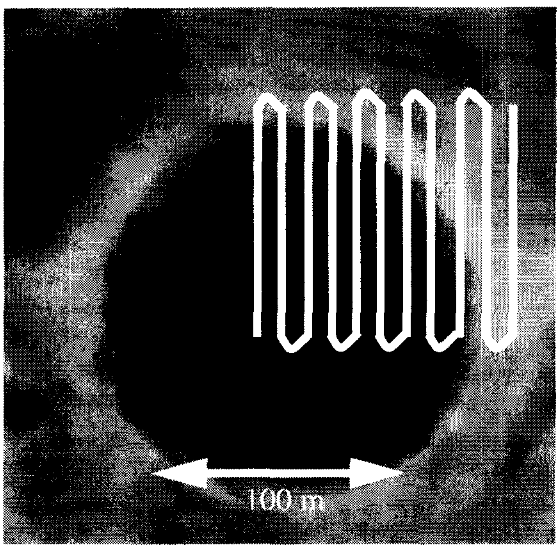

FIG. 4: Coverage Pattern over Crater

Traversibility of the region and the effect of slopes on robot locomotion and pose were not considered, as the purpose was to gain an understanding of the shadowing caused at different latitudes by the terrain features. The power generated by two back to back vertical solar panels and one top horizontal solar panel, each of size 1 meter square with a maximum output of 100 Watts, is calculated for latitudes of 85 S, 45 S, and 0, on December 1, 1999.

The Tycho crater is deep and abrupt, even with the scale reduced, as can be seen by the plot of vertical elevation versus time in Figure 5. This causes the robot to generate power sporadically, as it passes in and out of shadows. Even with the relatively high sun angles at the equator, as high as 68 degrees at this date, shadows still cover portions of the crater. The sun for this simulation was coming from the lower left quadrant of the image, causing the central peak of the crater to shadow the robot as it passes to the upper right of the peak on the second and third rows of the pattern. The rim of the crater causes more shadows during the final rows.

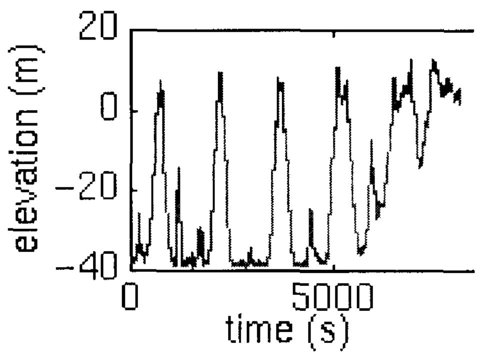

FIG. 5: Elevation of Robot during Pattern

Figure 6 compares the power generated at the three different latitudes on Earth. The x axis shows the time passed as the robot progresses through the coverage pattern, while the y axis shows the instantaneous power being produced. For lunar locations, with the moon's smaller curvature, distant terrain features will not occlude the sun as much. The lower sun angles at polar locations will counteract that effect, however, causing longer shadows.

5. ADDITIONAL CONSIDERATIONS

In the above simulations, terrain effects on robot locomotion and pose were ignored. In reality, a robot will not be able to drive straight up a steep crater wall, and any slopes will affect the relative angle between the sun and the robot's solar panels. Incorporating slopes into the simulation and calculating their effect on the robot's roll and pitch is the next step.

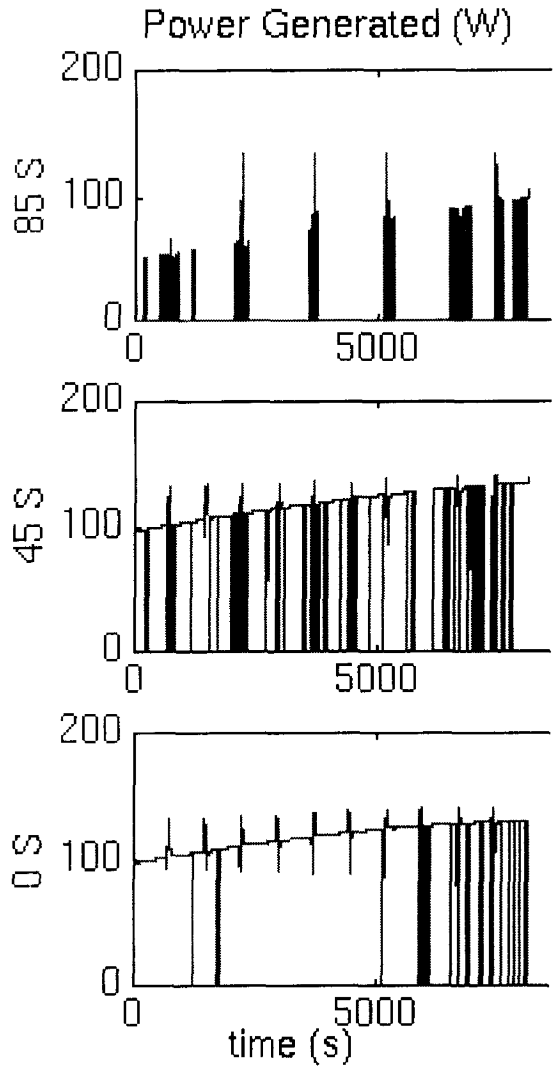

FIG. 6: Solar Power Generated within Crater

In addition, for uneven ground, uncertainties in the terrain will cause uncertainties in the power evaluations. Previously unknown obstacles will cause path deviations, and smaller rocks and hills will temporarily affect the orientation of the robot. Strategies for accounting for uncertainty include considering a range of possible locations and orientations of the robot, or taking actual field data and comparing it to predicted data, converting the observed variations into uncertainty.

Another consideration is the variation in the robot's power consumption. Not only does the amount of power generated need to be calculated, but also the amount of power consumed to ensure that enough power is available to accomplish the plan of action. The type of steering activity, the terrain to be covered, and environmental affects such as wind will all affect the power requirements of the system.

Different coverage patterns require different amounts of steering changes, thus requiring more or less power. Tests with the robot used in the Antarctic meteorite search show that nearly 4 times the amount of power is needed for a skid steered point turn than a 12 meter radius skid turn [Shamah]. Uneven or soft terrain may cause more slippage and power draw as well. Finally, the configuration of the robot may affect the amount of power consumed. Depending on the wind direction relative to the robot's heading, a vertical solar panel sail as described for the simulations will cause varying amounts of air resistance, and therefore variations in power consumption. However, for locations on the moon, and possibly Mars, wind will be irrelevant or negligible.

The two pattern types shown here are only a small sample of the plans that can be evaluated by the solar power expert. Patterns with intermediate amounts of curvature between the straight and spiral patterns can be developed. One such pattern is a polar sun-following pattern, where the robot turns continually to maintain the optimum orientation of its solar panels to the sun. Other patterns may be based on the terrain, such as boundary-following patterns. Creating a wider repertoire of patterns will be pursued in the future.

The simulations above demonstrate the capability for an on-board solar power expert, allowing the robot to make decisions based on the current environment. This software has, in fact, been implemented on the robot used in the Robotic Antarctic Meteorite Search project, which will be deployed for a second time in Antarctica in the 1999-2000 season [Shillcutt]. Solar power evaluations will be produced and compared to actual solar power generation based on observed sun visibility and test solar panels.

By evaluating multiple coverage pattern options with respect to power considerations, explorer robots can select the plan which allows the best chance of surviving. With the limited resources typical of space missions, even minor improvements in power usage can determine whether or not a mission is successful. Using this solar power expert's information to select the best plans will enable remote robotic explorers to extend their lifetimes and produce greater returns.

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TABLE 1: Simulation Results

Latitude	Season	Sun Elevation During Pattern (degrees)	Energy Generated Straight Rows, Side Panels	Ratio of Side / Top Panels (Straight : Spiral)	Ratio of Straight / Spiral Patterns
89 S	Summer	23.8 - 24.0	784,534 J	2.009 : 1.415	1.420
	Spring	3.9 - 4.1	857,086 J	12.624 : 8.884	1.421
	Winter	-	-	(sun not above horizon)	-
80 S	Summer	32 - 33	755,820 J	1.452 : 0.975	1.490
	Spring	12 - 13	880,349 J	4.152 : 2.774	1.497
	Winter	-	-	(sun not above horizon)	-
70 S	Summer	38 - 43	619,053 J	0.977 : 0.718	1.359
	Spring	18 - 23	791,702 J	2.283 : 1.626	1.404
	Winter	-	-	(sun not above horizon)	-
60 N	Summer	44 - 53	502,388 J	0.682 : 0.543	1.258
	Fall	19 - 27	733,628 J	1.887 : 1.449	1.302
	Winter	1 - 7	866,990 J	10.364 : 7.300	1.420
50 N	Summer	49 - 63	370,243 J	0.454 : 0.403	1.126
	Fall	26 - 37	700,281 J	1.352 : 1.002	1.349
	Winter	9 - 17	839,614 J	3.524 : 2.493	1.414
40 N	Summer	53 - 73	255,119 J	0.259 : 0.298	0.867
	Fall	32 - 47	605,869 J	0.959 : 0.736	1.303
	Winter	17 - 27	786,878 J	2.041 : 1.457	1.400