Task Evaluation for Robotic Explorers

Ph.D. Thesis Proposal

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December 2, 1998

Abstract

Robotic explorers of remote locations require autonomous capabilities to select the best tasks to perform. Successfully accomplishing their mission requires careful utilization of resources, particularly power. The robot must evaluate each potential task in terms of the power that will be gained from solar panels or other sources, as well as the power that will be expended by the performance of the task. The uncertainty of the evaluation helps determine the level of risk associated with the task. Major parameters to be considered are the terrain, orbital parameters of the sun, and the locomotion and power generation capabilities of the robot.

A primary goal of surface exploring robots is complete coverage of an area, so coverage patterns are a major task to be evaluated. The effects of each task on power and other resources, as well as on the fulfillment of the robot's goals, need to be evaluated and then weighted by the priorities of the resources and goals. The priorities are dynamically changing, depending on the current resource availability and on the goals to be accomplished in the robot's current mission stage. The weighted evaluations are combined into one equation, producing a rank for that task. The task to perform can be chosen based on the rankings of all available task options.

Motivation

Autonomy and Power Resources

Capable and adaptable robots are needed for exploring areas too dangerous or costly for humans to visit. Planets and moons, ocean floors, polar regions, and other remote earthly locations 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 is not viable either in remote areas, where time delays between the robot and human operators cause multiple difficulties. Rapid reactions to dangerous situations are not possible, limited sensor information is difficult for humans to decipher and react to, and multi-stage tasks are lengthened unacceptably. 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.

Reasoning about the probable results of actions is crucial for robotic explorers. These robots typically have limited resources, which must be used as efficiently as possible. To succeed in their mission of exploration, as much work as possible needs to be extracted out of few resources. These resources include power, such as solar panels, wind turbines or batteries; time; sensors; computer and other hardware 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 injected 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 their mission.

The most critical exploration resource is power, and optimizing its generation is crucial. For this class of remote, exploring robots, solar power is the mode of choice. 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, public and governmental approval which may take years to complete. Despite the 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 out 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 in a particular location 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.

The effect of terrain on sun visibility is an issue which requires more explanation. While planetary and lunar surface missions to date have been near-equatorial expeditions, polar regions are increasingly of interest to researchers. 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.

Given information about the environment and the solar panel configuration, robotic explorers can evaluate how a given task will affect the solar panel orientation and location, and therefore the amount of power generated. For robotic explorers, extensive travel around and through a region is a primary task, using complete coverage patterns. Evaluating such tasks requires a clear understanding of the changing relationship between environmental parameters such as the sun angle and terrain features, and the robot's location and orientation.

This generated power, whether used immediately or stored in batteries, needs to be used efficiently as well. The type of steering activity and the terrain covered will affect the power requirements of the locomotion system, so tasks need to be evaluated in terms of the steering activity and terrain which will be covered, as well as other power consuming activities. Additional power sources and other resources need to be carefully utilized and conserved as well. With proper evaluation metrics, the effect of robot tasks and actions on all relevant resources can be considered. These evaluations may not accurately reflect the true use and generation of resources that will occur when the robot enacts the tasks, however, so a measure of uncertainty must also be calculated. If the uncertainty is large enough, the robot may run out of power before completing a task, so the risk associated with committing to a given task will be based on this uncertainty.

Task Mediation

The more capable robotic explorers are, the more valuable they will be. As an extension of the human presence, robotic explorers should provide as much information as possible about the environment being explored. To this end, robots must be able to perform a wide variety of tasks, such as driving to a point, observing with high resolution cameras or radar, taking spectrometer readings, drilling or extracting core samples, and processing data that has been gathered. These mission related tasks can be separated from other survival tasks, such as turning on heaters or fans, and sensing and avoiding obstacles, which are not addressed in this proposal.

These mission tasks, in combination or separately, are used to meet more general goals, such as covering an area as completely as possible, searching for and evaluating new areas, classifying and identifying certain rocks or soil samples, evaluating the stratigraphy in a location, or performing other geological tests on rocks. The overall mission of exploration will involve one or more of these general goals. With multiple resources to optimize and multiple goals to achieve, robots must have some way of prioritizing their potential tasks.

Tasks can be evaluated both for their effect on the robot's resources and their effect on meeting the robot's goals. The distinction between resources and goals clarifies the effects for human operators or programmers, but the robot's planner need not distinguish between them. The criteria for selecting one particular task from a larger group of possible tasks depend only on the priorities of the resources and goals. One resource may be more scarce than the others, or one goal may be more important than another. The amount of uncertainty can also be evaluated for each resource just like the resources themselves, weighted by a priority based on the amount of acceptable risk. These priorities might also change over time, as the availability of resources changes, or as goals are completed and the robot's mission changes shape.

For example, a robot may have a mission of exploring a remote location to evaluate its usefulness to humans. Rough environmental information may be known ahead of time from remote sensing data, but the first stage is to map the terrain from the ground in a higher resolution. The goals in this stage are coverage of the area as completely as possible and searching for and evaluating new areas. The level of evaluation here is to determine areas which have high probabilities of various resources so that they can be further explored later if possible. Deviations from the pattern or detailed examinations of rocks are not generally desired at this time. The types of tasks that will be used in this stage are driving in a patterned search, observing with high resolution cameras, and processing the data to store in a map of the area.

When a specified area has been traversed with a broad coverage pattern, the second stage begins. This stage involves evaluating the actual presence and quantity of resources. Finer coverage of specific, smaller areas is desired, and many deviations from the pattern for closer examination of specimens will occur. The goal of coverage is still desired, but the goal of classifying rocks and soil samples is given a higher priority. After this stage is completed, the robot may move to a new area and begin with the first stage again.

Such dynamic missions, in dynamic environments, require flexibility in how robots evaluate and pick specific tasks to perform. When determining the best task to do next, each task can be evaluated in terms of resource utilization and effectiveness in meeting different mission goals. The priorities of goals and resources may change over time, so the planning system must take these priorities into account when selecting the best plan of action. Different mission stages will affect the priority of different goals and the amount of acceptable risk, low power situations will increase the priority of power resources, temporary unavailability of some resources will change the goals or resources allowed, and time constraints due to communication availability with human controllers will affect the priority of time required to complete a task. Allowing the priorities for each resource and goal to vary will allow robotic explorers more adaptability in responding to their environment.

Problem Statement

The evaluation of coverage patterns and exploration tasks with respect to power generation, power consumption, and other resources and goals will enable crucial improvements in the productivity and return value of robotic explorers. Many planners and schedulers for mobile robots have been designed, ranking discrete tasks in terms of optimizing costs or achieving goals. Coverage patterns and path planners have also been designed for various types of robots and missions, ensuring completeness or optimizing distance, curvature or other path features. Calculations of power generated by a particular solar panel configuration and given average environmental parameters have been made. Studies of power consumption in terms of terrain to be covered have been performed. However, combining all these factors, for the duration of entire coverage patterns and other tasks for surface exploring robots, with changing environmental parameters, is a topic which still requires further research.

Proper use of resources is essential for remote robotic explorers, particularly power generation, so optimizing resources such as solar power gain needs to be part of their planner. Terrain features, the apparent movement of the sun, the starting time of the path plan, the robot's location, the robot's orientation including terrain-induced slope, and solar panel configuration all need to be analyzed and combined for the duration of a path plan in order to generate an accurate evaluation of the solar power generation possible. The uncertainties in the evaluation then provide a way to appraise the risk associated with pursuing the task. Similar factors need to be considered for wind power generation, or other sources of power. Combining power generation then with power consumption, for a coverage pattern or other plan, considering the current environmental conditions, is required for a complete power evaluation.

For robotic explorers, each task needs to be evaluated with respect to all resources and goals of interest, the values being combined in a way which reflects the current availability of resources, desired goals, allowable risk and demands of the robot. Priorities of resources and goals may be changing with time, so a planner must be able to take into account different priorities. Combining the effects of a robot's actions on all issues of importance, the planner can then mediate between proposed tasks.

Problem Space

Robotic explorers have limited resources and multiple goals. They primarily operate autonomously, with only high-level goals defined and intermittent communication with remote operators. They have a limited repertoire of tasks, but these can be combined to form a variety of plans of action. One or more tasks will comprise a plan, which will be evaluated as to its affect on each of the robotic explorer's goals and resources. These evaluations are weighted by the current priorities of the goals and resources to produce a ranking of that plan. The planner does not synthesize new tasks and evaluate an unlimited variety of options, but rather, compares the rankings of a predetermined set of potential plans, mediating between them and selecting the best one for the current situation.

This general mission planner is adaptable to any number of goals and resources, and various types of robots. This thesis will concentrate on a specific class of robotic explorer with an emphasis on the resources of power generation and consumption. The class of explorer is a mobile surface robot, designed to explore remote outdoor locations by enacting coverage patterns and performing close-range sensor or contact measurements of target objects. Solar panels are the primary source of the robot's power, along with batteries to store energy. The solar panels will generally be fixed in place, although pointing panels, wind turbines or other power sources can also be considered. The areas to be explored are uncluttered and generally devoid of man-made structures. Priorities of goals and resources depend on the mission stage, the current state of power and time related resources, and any failures of goal accomplishment. A number of steps need to be addressed before plan mediation can occur:

- Formulate and describe the tasks of which the robot is capable
- Itemize the goals and resources which are relevant to the robot
- Develop algorithms for calculating the relationship of each task to resource utilization and goal fulfillment, and the uncertainties involved

  For solar power generation:
  - Develop algorithms for relating surface location to sun position, as well as Earth position for off-planet communication, as a function of time, for planetary bodies of interest
  - Merge locally generated map data with *a priori* large-scale terrain information
  - Combine sun position algorithm with terrain features to determine shadowing
  - Combine robot configuration and orientation with sun position and terrain shadowing to determine solar power generation
  - Develop heuristics for estimating the uncertainty of robot orientation and thus solar power generation, based on terrain and other irregularities

  For power consumption:
  - Relate path and coverage pattern plans to steering activity
  - Model robot locomotion to determine power consumption, and its uncertainty, as a function of steering activity and terrain
- Coordinate evaluation methods for all resources and goals, to enable evaluations and their uncertainties to be combined in a meaningful manner
- Determine a method or methods of setting resource and goal priorities for task mediation

Problem Assumptions

Fully developed robotic explorers contain many interrelated components, with multiple systems and capabilities which are required for complete functionality. This thesis only addresses a limited portion of these components, and thus many assumptions are made:

- Adequate localization of the robot exists, such as GPS or landmark navigation
- Adequate obstacle detection and avoidance exists
- Adequate locomotion of the robot exists, along with other control and manipulation functions
- Adequate sensor functionality and information acquisition exists for local map generation and target object localization
- A robust executing architecture and communication protocols exist
- Recovery from or compensation for failures of mechanical robot components and the detection of such failures are not addressed
- Exploration area is effectively in 2-1/2 D: area is a two-dimensional surface, although the effects of changes in elevation and slopes on sun angles, shadows and area coverage will be considered

Prior Work

Solar power concepts, resource optimization, navigation and path planners, coverage patterns, and mission planning architectures have all been studied to varying degrees. This section will describe the work done in each of these areas, explaining the relevant points which will be useful in this thesis research, as well as the points which remain to be addressed.

Solar Power

Several studies have been made of the material composition of solar arrays. Landis [36] describes the evaluation of several types of material based on the environment of Mars. The effect of latitude on available solar power is mentioned, but more attention is paid to the effects of dust, light spectrum, temperature, and the soil. An experiment to test five types of solar array material near the Martian equator is described in [54]. This experiment will take place on the Mars 2001 Surveyor Lander. An earlier paper by Landis and Appelbaum [37] also discusses the efficiencies of solar array materials, and various projects which could utilize solar power on Mars. In addition, this paper provides graphs of the number of daylight hours as a function of time of year and latitude. Polar latitudes generate the worst-case scenario, with times during the year when no sunlight is available. However, these papers primarily concentrate on the physical aspects of solar arrays, and not the dynamic evaluation of power generated by a single solar panel configuration.

The optimum angles for deployed solar arrays on Mars or on the moon are the topic of two papers by Anthony Colozza. In [12], Colozza describes the deployment of a stationary tent-shaped array. The desired energy profile is flat, generating a constant amount of power. A tent angle of 60 degrees is found to be best, assuming the sun passes directly overhead, which is too much of a simplification for the needs of this thesis. In [13], a tracking array is studied, comparing the gain of generating more power with the costs of consumed power, mass, volume, implementation time and reliability of the array. In both papers, more details about the composition and mechanical configuration of the arrays are described than the actual evaluation of solar power gain over time.

Three papers discuss the modeling of solar power input and output for proposed and actual missions. McKissock et al. [44] discuss the power requirements for a forty day human mission in an equatorial location. The solar model used has equal amounts of sun and darkness, and the solar arrays considered are fixed. Ewell and Burger [19] describe the solar array power model for Mars Pathfinder. This models the power produced by the lander, based on the latitude of the landing site, the orientation of the lander, the time of year, and the atmospheric and temperature conditions. Shadowing by the rest of the lander is considered as it changes throughout the day, but the lander itself is not mobile. The authors state that the sunlight model used is “too crude an approximation...especially for missions near the poles.” So while the concept presented here of modeling how much power can be produced is relevant to this thesis research, the actual implementation is not applicable to a mobile rover at an arbitrary latitude. A review of the power components of Mars Pathfinder is given in [58]. They used the model discussed in [19] to provide some of the input for the power subsystem model, which takes the optical depth and intensity of the sunlight, the tilt and shadowing of the solar array, and the amount of power used to predict the status and voltage of the lander battery. Again, this work is relevant to this thesis, but does not consider a mobile rover, or tasks such as coverage patterns.

Studies of solar power in polar latitudes are more limited. A study was made of the trade-offs between cost, complexity and power generation for a fixed versus tracking solar panel for the Mars Polar Lander [64]. The fixed panel was chosen, despite the existence of long shadows at the lander's proposed site of 73 to 78 degrees south latitude. Instead of panels tracking the sun, the lander will be preprogrammed to touch down in an orientation which optimizes the amount of sunlight incident on the panels and limits the amount of shadowing caused by the rest of the lander body. In the technical report detailing the design of a lunar polar rover [15], the appendix describes calculations of solar elevation for polar latitudes on the moon, as described in the work to date section of this proposal. Some description of terrain effects is also given.

The work most relevant to this thesis proposal is described by Bresina et al. in [4], where the use of solar power resource information in the planning process is suggested. Shadowing, continual assessment of resources, and updating the utility of plans based on environmental and resource changes are all mentioned. The power profile described includes estimations of solar exposure, the tilt of the terrain, and risks associated with uncertainty. Choosing a particular step to take in a general plan, the concurrency and order of tasks, and scheduling of various resources and tools are the main contributions. Remote Agent considers maximum resource needs of discrete tasks to guarantee that enough power or other resources are available for each task. Selecting whether or not a task should even be performed is not the goal of this architecture. This work does not develop an actual algorithm for sun angles, or for sun and terrain interactions, as part of a rover on-board system. Other power sources such as wind have not been considered either. Coverage patterns are not considered, and neither is the selection of a specific path or pattern based on the position of the sun to optimize the generation of power.

Resource Optimization

Planning to optimize resources is a prevailing concept in robotics research [22]. Some research deals with specific ways to optimize a particular resource, and other research has developed more general architectures which include resource management and optimization. Dorais et al. [18] describe two such architectures, Remote Agent and 3T. 3T primarily deals with scheduling of resources, and can detect events such as when a resource reaches a certain threshold or is depleted. Remote Agent can ensure that resources are not depleted ahead of time, but mainly manages discrete resources which are already present, as opposed to ways to generate new resources. Remote Agent was implemented on the Deep Space 1 mission [24]. This paper discusses more of a software engineering perspective, managing abstract resources as discrete objects, and using resource locks to manage conflicting demands. The adaptation of Remote Agent to planetary rovers is described in [4]. The ability to continuously assess the capacity of resources and to predict the demand for them allows dynamic resource allocation and scheduling, optimizing their utilization. The resources and tasks considered are more discrete than would be considered for evaluation of long-term tasks such as coverage patterns, however.

More specific resource optimization is used in calculating optimal space trajectories. [65] describes planning for minimum fuel rendezvous trajectories in space, optimizing the amount of fuel and the number of thruster firings. Optimal trajectories for motion between two co-orbiting objects is described in [50]. This problem is coupled in time and distance, so numerical methods are required to solve for the optimum solution. Based on multiple cases, heuristics for near-optimum trajectories can be developed. Though the environment is different than that considered in this thesis proposal, the use of heuristics may be helpful in quickly calculating resource utilization estimates for long-term coverage patterns in the presence of uncertainties. A two-dimensional version of trajectory calculation optimizes distance, time and fuel in the presence of dynamic environmental changes which necessitate replanning from time to time [45]. Similar replanning may be necessary for the scenario considered in this research proposal, due to plan deviations.

More general approaches to plan optimization are the A* and D* algorithms. D* is described by Anthony Stentz in [60, 61, 62]. This optimal path planner incorporates new environmental information as it becomes available. The cost function often used is based on distance, but any similar cost function can be used, where the cost from a particular point to the goal can be calculated or estimated based on currently known information. [6] uses D* with multiple robots and multiple goals, with the environment becoming gradually better known with time and exploration. Though this algorithm can be used in some aspects of the path and task planning for this thesis proposal, the evaluation of costs pertaining to solar power generation still needs to be developed.

Navigation and Path Planners

Navigation in outdoor environments and planning of paths are each topics that have generated a multitude of methodologies and papers. Latombe's book [38] reviews many of the approaches that have been studied. For the purposes of this thesis research, several related subjects can provide useful background knowledge.

One subject is the formulation of maps to use in representing the environment and in planning paths. Maintaining complete and high resolution information about the robot's environment is difficult and resource-intensive, but multiple ways to consolidate the information have been developed. Brooks first suggested representing the obstacle-free space with geometrical cones [5]. Other methods are the visibility graph, based on the vertices of obstacles [39, 53, 70], the Voronoi graph, based on the distance from obstacles [10, 53], and cellular decomposition, dividing the area into variously shaped regions [14, 53, 34]. A uniform grid cell is also a common representation [40], where the grid resolution can be chosen to reflect the size of obstacles or the robot [14].

For all these types of maps, certain useful points can be selected, such as meetpoints where all nearest obstacles are equally distant, nodes situated between obstacles at defined distances, or lines of points separating obstacles. Maintaining only this point information further consolidates information about the environment, allowing a concise graph, such as a quadtree, to be built. This graph can be searched to pick a sequence of nodes to follow through the environment [40, 70]. The best paths between each node can be determined beforehand. For known environments, a complete map can be built ahead of time, but unknown environments can be mapped incrementally, using sonar, vision, or other sensors.

Algorithms for searching a graph or map are another useful subject. One of the primary considerations in finding a path is avoiding obstacles, so by limiting the path search to free space areas, collisions can be avoided. To guarantee that the path is wide enough for the robot, many maps are built with "expanded" obstacles, or configuration space [55]. Aside from collisions, the length or cost of a path should be optimized as well. Several algorithms can search a map and produce a minimum cost path, such as A* [28, 39, 53], D* for when the world is not completely known or is changing [61, 62], and distance wavefront propagation [14, 27, 70]. The cost function used in these approaches can be not only distance, but can also include a discomfort cost of being too near obstacles [68], a value describing terrain difficulty, the number of maneuvers required [28], visibility of a landmark, or amount of uncertainty [29]. Another way to avoid obstacles is to use a potential field technique, that provides a "repulsion" factor to steer the robot away from dangerous areas [67]. A common failing of this technique is the production of potential field minima which trap the robot. One approach uses a genetic algorithm to effectively generate a random search when the robot is temporarily trapped in this way [55].

A non-optimal, but guaranteed path can be found by using a "Bug" algorithm. This algorithm guides the robot straight to the goal, and when an obstacle is encountered, the robot follows rules which guide it around the obstacle [39, 42, 43]. A different approach, utilizing qualitative information and a human-based idea, is to plan a route with multiple levels, similar to picking major highways to get from one city to another, then picking the local roads which lead to a particular location within the city [26]. Another multi-layered approach depends on the type of environment. In simple areas, the robot just reacts to the immediate environment. In more complex areas, a two dimensional map is utilized, and in the roughest terrains, a three dimensional map incorporating elevation is required to ensure the robot can safely travel from point to point [8, 9].

The methods above can select complete paths or just waypoints for the robot to use as subgoals. Calculating a precise path to follow and maintaining that path is another subject. Straight line paths between waypoints can be smoothed or modified to better enable robots to follow them [17, 27, 57]. In very rough terrain, each point along the path may need to be checked to guarantee that the robot can be safely positioned in that location [28, 29]. To maintain a given path, the robot needs to know where it is. Dead reckoning can provide a rough estimate, while a human operator or landmarks can provide a more accurate fix from time to time [29, 33, 43, 69]. In fact, a range of human interaction can be utilized, from complete teleoperation to complete autonomy [67].

The details of all the above techniques are described in the referenced papers, along with descriptions of their implementation on real robots. This review simply indicates that a large body of work in this area already exists and can be utilized for this thesis research. Path planning and navigation are not the focus of this proposal, but are instead a platform upon which path and task evaluation can be built.

Coverage Patterns

Coverage patterns are a main topic in this thesis proposal, and many researchers have concentrated on this field. The most common type of coverage pattern is the straight rows pattern, where the robot sweeps up and down parallel lines [7, 11, 32, 33]. Obstacles are handled in various ways. In [11], the search area is decomposed into cellular regions, each of which contains no obstacles. The robot performs the straight rows search in each region, using a calculated sequence of moves to optimally link the regions. In [7], when obstacles are sensed, the robot follows the obstacle boundary until the other side is reached, and then continues the search pattern. Similarly, rules are defined in [32] for where the robot should move when an obstacle or sub-inlet is detected, producing an optimal coverage pattern in terms of distance so that minimum overlap occurs. The floor cleaning robot of [33] has several options for turning around when obstacles are encountered or at the end of rows, based on the width of the rows and the capabilities of the robot.

Another type of approach is the contour following pattern [35, 69]. The coverage area is divided between multiple robots in [35], with each covering an area by following its contours. The extension into small corners is done by following a Voronoi diagram. [69] uses a distance wavefront propagation in a grid representation of the environment. The robot starts by moving through all grid cells with the smallest value, moving up to the next higher valued cells after that, and so on. This produces a contoured path surrounding the starting point.

Random searching may be more beneficial than an exhaustive search in some conditions, such as mine-sweeping, where minimizing the number of unseen targets in a limited area is a higher priority than maximizing the total number of targets found [23, 31]. Knowledge of the prior probabilities of target locations also can affect how efficient a given search pattern is. Animals, for instance, tend to follow heuristics more than exact rules when searching for food, as if they were incorporating the effect of uncertain target location probabilities [25].

The evaluation of pattern efficiency is addressed in [23], [31] and [33]. Hofner and Schmidt, in [33], evaluate their floor cleaner's patterns after completion, based on the total time required, the amount covered out of the specified area, the amount of overlap in covered area, and the floor space covered per hour. However, no research to date has evaluated coverage patterns based on the amount of solar or wind energy that could be generated by following the pattern, or has calculated directly the amount of energy that has been expended. The types of coverage patterns studied in the literature is also very limited, compared to what is proposed in this thesis research.

Mission Planning and Agent Architectures

Agent architectures provide a framework for mission planning, deciding when to do which task. Nearly all architectures have multiple layers, such as a functional level which controls the actual hardware, a planning level which decides what to do when, and perhaps an executive level which converts a plan into specific actions. One architecture which fits this description is the Remote Agent, or RA, developed by researchers at NASA's Ames Research Center. RA was originally designed for spacecraft such as Deep Space 1 [2, 18, 48, 49, 51, 52]. The top layer of this architecture is the Planner/Scheduler and Mission Manager. Human operators give high level goals that need to be achieved in a certain amount of time, while the planner uses temporal reasoning to determine in which sequence actions need to be taken. Expert subsystems can be used to provide information to the planner, such as the amount of resources that will be consumed during a certain action. The second layer is the Smart Executive, which can select among different ways to accomplish a task given to it by the planner, and requests that the actions be executed in the proper order. It communicates with the third layer, Mode Identification and Reconfiguration. This is a more reactive troubleshooter which checks to ensure that errors do not occur, and determines what to do if they do occur. Any uncertainty is handled by assuming the worst case.

The spacecraft domain considered for RA has many differences from the mobile robot domain, such as a simpler environment. Current work plans to adapt RA for rovers [4]. This adaptation will consider resource utilization based on estimated profiles of the capacity and demand for the rover's resources. The Smart Executive's choice of which task decomposition to pick can be based on a utility value, updated to reflect the environment, current resource availability, and the system state of the rover. Ways for handling environmental uncertainties and the allowable risk are also being studied. The areas which this work covers as opposed to the work proposed for this research were discussed in the solar power subsection previously.

Another agent architecture is 3T, which is being developed and implemented in work at NASA's Johnson Space Center [3]. [18] suggests that this architecture might be effectively merged with the Remote Agent, combining the best properties of both, such as RA's resource management and 3T's user interactivity and adjustable level of autonomy. 3T also has three layers, the planner, the sequencer, and the skill manager. The planner takes a high level goal, reasons about goals, resources and time constraints, and produces a partially ordered sequence of tasks. The sequencer takes each task and decomposes it into detailed steps necessary to accomplish the task. This layer monitors the state of the world, stopping or starting actions when required. The skill manager contains the actual interfaces with the hardware for each action.

3T has been combined with a Generic Scheduler/Rescheduler for use in crop planning for life support systems [41]. The scheduler reasons about time and dynamic changes in resource availability, including long-term dynamics that are part of a system such as planting crops. User interaction is allowed at various levels, such as manipulating the weights in an objective function used to select the best task. Replanning occurs when significant deviations from the plan are observed. In [6], replanning occurs when new information about the environment is obtained. This planner uses D* to select the best paths for multiple robots traveling to multiple goals. In some cases, the planner reorders which robot should travel to which goal. Both these papers address dynamic evaluations, but specific tasks or goals are the primary consideration, as opposed to long-term coverage patterns which have a continual affect on power generation and consumption.

Two other architectures of note are the Task Control Architecture [59], and the architecture developed at LAAS-CNRS in France [1, 8, 9, 16, 66]. The Task Control Architecture, or TCA, provides a framework for control and management of multiple processes, hierarchical task decomposition, sequencing and scheduling of actions, resource management, activity monitoring and error recovery, and interprocess communication. Algorithms for specific robots or tasks, such as path planners or real-time interfaces, are not included in TCA. The LAAS architecture has three layers again: decision, execution and functional. The decision layer is primarily a temporal planner using the IxTeT software to roughly schedule tasks. The PRS software further refines the tasks by selecting from among a library of plans and procedures which can be enacted. Similar to the work proposed here, synthesizing original plans is not done. The execution layer uses Kheops to produce executing code from a set of logical rules, providing a link between long scale planning and short term action. The functional layer controls the hardware to interact directly with the environment, using action modules generated by GenoM. Resource management is done at the planning level, dealing with the predictable part of a dynamic environment. Primarily access to hardware resources and amount of available power are the resources which are considered.

The research proposed for this thesis could fit in either at the decision or execution layers of the above architectures, depending on how the layers are defined. The power evaluation scheme proposed is similar to an expert subsystem used in the top decision layer of the Remote Agent, providing specific information about tasks to be accomplished. Deciding in which order tasks should be executed can be placed at either the top or middle layer of the architecture. Details about how tasks are to be executed are not part of this proposal, though implementation through the actual robot level, using existing work, is planned.

The evaluation of tasks is the main focus of this thesis proposal, and several other papers deal with this or related topics. The author's prior research addressed modules based on costs and benefits for evaluating tasks [56]. Similarly, Sukhatme and Bekey used a weighted evaluation of multiple criteria to pick the best design for a physical rover [63]. Farritor described several uses of modular evaluations, combined with a genetic algorithm, to pick the best plan of action [20] or the best robot assembly [21]. All of these modular systems are similar in approach to evaluating tasks based on multiple criteria. A "systematic, quantitative performance evaluation" for planetary rovers is described in [43]. This was an evaluation of different physical rover types for a single given task instead of an evaluation of multiple tasks. Finally, Morignot and Hayes-Roth describe a motivational profile that is used to determine which task a robot should perform [46, 47]. The profile is a set of weights indicating the importance of five different attributes, including physiological needs such as power and the desire to learn and explore the environment. The profile weights can be adapted depending on the environment or human operator choice, and a linear combination of the weights determines which task is the best to perform. Solar power, wind power, and coverage patterns are not considered here.

Technical Approach

Several major categories of a robotic explorer's mission need to be studied and developed before the robot will be able to make an informed decision about which tasks to perform. This section will describe these categories which are needed for an effective mission planner. The information gained by each category will be highlighted, and the development strategies which will initially be explored will be given, though alternate strategies may become more relevant as work on this thesis progresses.

The overall definitions and purposes of the categories are generalizable to many different classes of robot, with many different missions. However, one particular robot class will be emphasized, an example of which is described below in the scenario. More general definitions of each category, the information they provide, the approach strategies and steps, and generalizations of the categories will be discussed following the scenario. The mission planner component will then be described.

Scenario

Coverage of an area is a common theme in several applications, whether pursued robotically or by humans. Searching for landmines in order to guarantee the safety of an area, or demining, is one such application. Another is searching for fossils as a record of the history of an area. The third application which is discussed here is searching for meteorites. 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, with little melting or surface erosion to hide meteorite falls. The extreme conditions also make it difficult for humans to work there, but a robot designed to explore this area could provide great scientific returns.

The tasks associated with an Antarctic exploring robot include performing coverage patterns to fully search an ice field and insure that all potential meteorites can be spotted. When a potential target is spotted, the robot must drive to that target, maneuver itself so that the target is within a particular sensor's workspace, and then use the sensor to take a reading of the target. Processing the sensor readings and calculating the probability of the target being a meteorite are other required tasks. These tasks must be evaluated with respect to various resources and goals.

The generation of power is a vital resource for a solar or wind powered robot. Both these power sources depend on the location and orientation of the robot while performing a given task. In the polar regions of Antarctica, the wind is often from a particular direction, so knowing this primary direction will enable planning the future generation of wind power. The future position of the sun can be calculated even more precisely, allowing a evaluation of solar power gain to be made. The amount of power consumed while pursuing a given task is also a resource to be considered. The power consumption will depend on the types of terrain to be covered and the type of steering activity required to follow a given task or plan, as well as the power required to use a given sensor. Computing resources and time required to complete a task are other resources to be evaluated.

Different goals of the robotic explorer are met by performing different tasks. One goal could be to completely cover an area, or in other words, to minimize the amount of uncovered area. Another goal could be to optimize the area coverage, or minimize the amount of area covered more than once. Minimizing the uncertainty of a target's classification, to determine as closely as possible whether or not a target is a meteorite, is another potential goal. The goal of survival is the most crucial, however, which includes generating enough power to remain functional.

Category Analysis

Tasks

A robotic explorer's repertoire of tasks determines its abilities and usefulness in accomplishing a given mission. These tasks include coverage patterns, driving to a waypoint, maneuvering to a certain orientation, communicating with remote users, processing data, using a manipulator such as a drill or a scoop, and using a sensor such as a panoramic camera, stereo cameras, high resolution cameras, spectrometer or magnetometer. The coverage patterns which can be followed include a straight rows pattern, a spiral pattern, a curved or sun-following pattern, or even a random pattern. The ability to robustly perform these tasks is already assumed in this thesis, as a foundation upon which task evaluation and mediation can be built.

The information provided by the descriptions of these tasks needs to be sufficient to evaluate the tasks' effects on the resources and goals of the robot. For example, the location and orientation of the robot at discrete time intervals throughout a coverage pattern is needed to calculate the potential solar power generation. The time and power required to accomplish the task are other facts which need to be described. The details needed in the task description will depend on the resources and goals of interest, but providing a set of general facts such as listed above will be sufficient for the majority of tasks.

The primary tasks which have been addressed in the work done to date are several coverage patterns and driving to a waypoint, all of which involve driving over an extended period of time. These tasks were approached by describing the position and orientation of the robot at each second of the total time required to accomplish the task. This information is used to calculate the task's effect on the resources of time and power generation, and the goal of area covered. This assumes certain information about the robot's configuration is known, such as the availability and configuration of power sources, the locomotion capabilities of the robot, and the extent of sensor coverage. Information about the external availability of power is also needed, such as the position of the sun over time. These are aspects which are defined as part of the resources category.

A study of the effect of terrain on these tasks is still needed, as is a study of the uncertainties in the evaluations. Some of the terrain factors that affect uncertainty are previously unknown obstacles which will cause path deviations, and smaller rocks and hills which will temporarily affect the orientation of the robot. One strategy for determining the uncertainty is to consider a range of possible locations and orientations of the robot that might occur, given the terrain and locomotion capabilities. Another strategy is to take actual field data and compare it to predicted data, converting the observed variations into uncertainty. Combining *a priori* terrain knowledge with a locally generated higher resolution map remains to be done, both for path planning purposes and resource and goal evaluations. Characterizing the steering activity of various patterns and paths is also needed. Other tasks that remain to be developed and described are additional coverage patterns, maneuvering, communicating and using sensors and manipulators.

In order to generalize the work in this thesis to other classes of robots, additional tasks and descriptions can be considered. The structure of maintaining certain information about each task, to be evaluated in terms of the resources and goals described later, will still be effective for many classes of robots.

Plans

The robot must choose a single plan to enact, out of a limited number of possible plans. These plans are just combinations of one or more of the tasks described above. Examples are coverage of an area with a certain sensor, which combines a coverage pattern with a continual sensor measurement; classification of a rock or soil sample, which includes driving to a waypoint, maneuvering, taking a sensor measurement or using a manipulator, and processing the data; classifying a series of rocks or soil samples; analyzing a site, which adds processing data to the area coverage plan; and sending results to a remote user, which combines driving to a waypoint where communication is possible and then communicating. The tasks involved in a plan will either be sequential, or if simulataneous, the combination will be guaranteed to have no resource conflicts. Each plan will combine the evaluations of its component tasks, producing a ranking for that plan which will be supplied to the mission planner.

The current strategy is to define a set of plans ahead of time which are to be considered by the mission planner, as opposed to generating new plans or even tasks during the mission. Consideration of unlimited permutations of all tasks is a difficult planning problem, and not addressed by this thesis. Only certain permutations are even relevant to or sensible for a given mission. One plan which can remain open ended is the classification of a series of rocks or soil samples. The locations and numbers of nearby target objects are determined only during the mission, and so cannot be defined ahead of time. Visiting the targets in various orders can be considered as separate plans, though heuristics can limit the number of permutations of target order to a reasonable subset.

Resources

The resources which are available and important to a robotic explorer will determine how the tasks and plans are evaluated. Typical resources to be considered are solar power, wind power, stored power, time and computing resources. The power to be consumed, either by locomotion, sensors or other devices, is effectively a negative resource, taking away the resources of solar, wind and stored power. The definition of the resources will depend on the configuration of the robot and its abilities, or in other words, the tools and power sources which are a part of the robotic explorer.

The information to be gained through this category is the evaluation of tasks. An algorithm for each resource calculates the gain or loss of that resource which will occur as the result of enacting a task. This gain or loss can be expressed in various ways, as long as the value is uniform in some sense so that a comparison between different tasks can be made for the same resource. The evaluation must also be comparable for different resources or goals, since a loss of one resource is worth a certain gain of another resource or goal. This need for uniformity and comparison is discussed further in the mission planner subsection.

One strategy for determining how to normalize the task evaluation is to calculate the percentage of gain or loss relative to some fixed maximum. For example, given the solar panel configuration of the robot, the maximum amount of power gain is fixed. In non-optimal situations, such as when the panels do not directly face the sun, the amount of power gain will be some lower percentage of the maximum amount. For a certain path and period of time, the total energy gained will be some percentage of the maximum which could have been gained. This percentage can be used as the evaluation of that task. Another option would be to just use the total power gain as the evaluation, and to determine how to normalize different evaluations only after all tasks and plans have been evaluated. In this case, normalizing the evaluations would be the job of the mission planner, and would be based on all available information about all the plans being considered. With either option, the uncertainties involved with the evaluations must be taken into account. Either a range of values will be determined, or a separate uncertainty value will be produced.

Several pieces of information must be known before a resource evaluation can be made. As stated previously, the configuration of power sources is one major component. The size and efficiency of the solar panels will determine how much solar power can be generated. An algorithm to determine the position of the sun as seen from the surface is another needed component. Preliminary work has already been done in this area, as described in the work to date section of this proposal. Merging this information with terrain features to determine shadowing, and then with robot configuration and pose to determine power generation, is the final step. For the power consumption resource, the amount of power used for locomotion in different terrains and with different steering activities, and the power used by sensors or other equipment, needs to be known. Tests to determine some of these values for the current robotic testbed are now being performed.

To generalize to other classes of robot, additional resources can be considered. For example, the resource of cargo space may be relevant for a robot designed to work in a warehouse. Pursuing a plan to load multiple packages before reaching the unloading dock would require consideration of how much cargo space the robot has available. A multiple robot scenario could consider each robot as a separate resource or set of resources. The relationships between the resources would be more complicated, but the method of evaluating tasks based on resources could still be used.

Goals

The goals of a robotic explorer describe the desired effects of tasks in accomplishing the robot's mission. Some goals to be considered are the amount of area covered, the amount of area covered more than once, classification of target rocks and soil samples, communication of data and results to remote operators, and analysis of a site's potential future use.

The information provided by this category is similar to that provided by the resources category. An algorithm will evaluate how well a given task accomplishes the goal, calculating some value which describes the effectiveness of the task. Again, this effectiveness must be expressed in a uniform or normalized manner so that the evaluations of different tasks can be compared.

An example of the strategy currently being considered is an evaluation of the amount of area covered. The amount of area that a particular coverage pattern covers will be a percentage of the total area desired to be covered. This percentage can be used as the evaluation. Another type of evaluation is for the classification of a target rock. The use of a sensor on a rock will improve the certainty of what type of rock it is, where the amount of improvement is related to the information gain of obtaining that sensor reading. Different sensors will provide different information gains for different targets, so the gain can be used as the evaluation for the goal of rock classification.

Other classes of robots will have additional goals. Again, as with the resources, goals can simply be added to the planner. With tasks properly described to allow the goals to be evaluated, the list of goals can be modified to fit any type of mission profile. Minimizing the time to sort and handle packages could be a goal for a warehouse robot. Ensuring that every mine is detected could be a goal for a demining robot. Any goal that can be adequately defined for a numerical evaluation to be produced is acceptable.

Mission Planner

The mission planner is the highest level considered in this thesis proposal, organizing the evaluation and selection of plans. As described earlier, the mission planner does not generate new plans, but only evaluates a predefined set of relevant plans. Each plan is separated into its component tasks. Each task is then evaluated with respect to the resources and goals which it affects. These evaluations are weighted by the respective priorities of the resources and goals, producing a ranking of that plan. The plan ranks are then compared, and the highest ranking plan is selected as the one to pursue.

Several details need to be considered in addition to the overall scheme stated above. The evaluation of resources such as solar power depend on the timing of the task, so a starting time is needed. If a sequence of tasks are being considered, then the starting times of each task must be determined to be used in the evaluations. At the beginning of the mission, the robot can select a predetermined activity, such as a coverage pattern, evaluating alternate tasks only after the robot is in motion. An underlying mechanism for switching between tasks is assumed, such that the previous task or plan can be halted cleanly, and the new task initiated.

Another detail is the uncertainty of evaluations, which can be handled in several ways. If the uncertainty of an evaluated task is reflected by a range of values, then the level of acceptable risk can be used to pick which value out of the range to use. If the acceptable risk is low, for example, then the value which reflects the worst-case scenario should be used. Higher risk levels indicate that a more optimistic value can be used. Another way to handle uncertainty is to treat it in the same way as a resource or goal. In other words, different tasks will result in different amounts of uncertainty for each resource. The amount of uncertainty can be evaluated in addition to the resource itself, weighted by a priority based on the amount of risk allowed.

The selection of the priorities of the resources and goals is another important research item. Initially, the priorities can be set ahead of time, based solely on the robotic explorer's mission. A human operator can also reset the priorities at any time. However, if the priorities are to change with the changing environment or mission stage, then a way to relate the changes to the resource and goal priorities needs to be developed. The priorities can be simply based on the importance of each resource and goal, so changes in the mission stage will lead to changes in goal priorities, and changes in resource availability will lead to changes in resource priorities. Care still needs to be taken in setting the priorities so that increases and decreases in different task evaluations are comparable and reflect the true preferences for the tasks, both for the same resource or goal, and across different resources and goals. Similarly, care must be taken in determining how the values are normalized.

For example, consider a task for which the evaluation of resource A is 0.8 and the evaluation for resource B is 1.0. A second task has an evaluation of 1.0 for resource A and 0.8 for resource B. If the priorities of A and B are equal, then the planner will decide that these two tasks are equivalent. If the priority of resource B is greater than that of resource A, task #1 will be preferred. However, consider a third task which has an evaluation of 0.8 for resource A and 0.9 for resource B. If all that is known is that the priority of resource B is greater than that of resource A, then this task will definitely be less preferred than task #1, but it could be either better or worse than task #2, depending on the actual values of the priorities (see Table 1 below). The priorities and evaluation normalizations need to be coordinated so that the final rankings accurately reflect the desired outcomes.

Resource Priorities	Task #1 0.8A + 1.0B	Task #2 1.0A + 0.8B	Task #3 0.8A + 0.9B	Task Rankings
A = 5, B = 5	*9.0*	*9.0*	*8.5*	1 & 2 tied, 3
A = 4, B = 5	*8.2*	*8.0*	*7.7*	1, 2, **3**
A = 1, B = 5	*5.8*	*5.0*	*5.3*	1, **3**, 2

Table 1: Resource Priorities and Task Rankings

One final consideration for evaluating plans is how to sum the rankings for the component tasks. Different plans may have different numbers of tasks, so summing the individual rankings will not work generally. Averaging the rankings is one option. Another option is to combine the evaluations for all component tasks within a given plan, for each resource or goal. Then weight and sum these combined evaluations just as if the set of tasks were a single task, producing a single ranking for the entire plan.

Reevaluating plans may be needed for two reasons. One occurs when deviations from the current plan grow large enough for the plan to become out of date and irrelevant. By keeping track of the expected position of the robot and comparing it to the actual position over time, deviations that exceed a threshold can trigger a new evaluation cycle of the mission planner. Another reason for reevaluating is that an alternate plan may become more desirable than the current plan. If one plan is to leave a coverage pattern to investigate a rock sample more closely, then that plan may not become desirable until the robot has moved closer in the pattern to that rock. One strategy is to consider such plans only when they become relevant. For instance, only when a new rock sample is detected or comes within a certain range should a plan to go to that rock be considered. Another strategy is to maintain a list of currently relevant plans and evaluate the plans intermittently. A variation of this strategy is to keep the initial ranking of the current plan, and only rank the alternate viable plans at given time intervals. Once an alternate plan surpasses the current plan's rank, the new plan can be initiated.

Work to Date

Simulations of several coverage patterns have been performed, along with evaluations of these tasks for a selection of resources and goals. Two coverage patterns, waypoint and sensing tasks have been implemented and tested on the Nomad robot. In addition, an algorithm to calculate the visibility of the Earth and the sun from the lunar surface has been developed.

Refueling Simulation

The earliest work involved a rows pattern, with the additional requirement for the robot to halt searching and return for refueling when needed. The purpose of this simulation was to investigate the cost trade-offs of developing a single type of searching robot that had to return to a fixed fuel depot versus developing two types of robots, one which would search for meteorites and one which would follow along more slowly as a mobile fuel station. For the purposes of this research, the relevance is the evaluation of the fuel and time costs of the patterned search plan.

Without the mobile fuel station, the searching robot spent almost as much of its time and fuel returning for refueling as it did searching for meteorites. The simulation evaluated two searching robots covering an ice field 5 km by 7.5 km, with 10 meter swaths covered with each row. The searching robots are assumed to travel 100 cm/s, 24 hours a day, with 6 gallon tanks and a 3 km/gallon fuel efficiency. These values were roughly based on the capabilities of the Nomad robot. The mobile fuel station travels at the same speed and with the same efficiency, but with an extra tank of 36 gallons to use for refueling. The mobile fuel station must still return to a fuel depot when it runs out of gasoline. Without a mobile fuel station, the robots require 2,050 gallons of gasoline and take 142 days to cover the area. With the mobile fuel station, the robots, including the fuel station, only require 1,324 gallons and take 87 days. Simulations were run with different size fuel tanks for the searching robots, from 4 to 12 gallon tanks.

Sun and Wind Power Simulations

Simulations of five different coverage patterns were made for a polar Earth environment. These coverage patterns were simulated for a 24 hour period, while the power spent driving, the distance traveled, the area covered, the power gained from two types of wind turbines, and the power gained from two solar panel configurations were all determined. Calculations were then made to find the percent of the total area covered which was covered more than once, and to find the percent of the area within a bounding area which went uncovered. These evaluations were then used to determine which type of coverage pattern would best meet the robot's goals, which were some combination of maximizing wind or solar power gain, minimizing re-coverage of an area, or minimizing amount of area uncovered.

Assumptions about the robot's environment allowed several simplifications. The sun was assumed to be visible at all times, rotating around the horizon at a constant rate such that it returned to its starting point after 24 hours. The elevation of the sun was taken to be just enough above the horizon to be in line with the robot's vertical solar panels, to simplify the calculation of the sun's incidence angle on the panels. The wind was assumed to be of constant speed and direction. The area being covered was flat and had no obstacles. The robot traveled at a constant speed at all times and never deviated from its path. Power consumption did not depend on any parameters other than distance traveled.

Four configurations of the robot's power generating capabilities were evaluated. One was a two-sided fixed solar panel, positioned as a vertical sail on top of the robot. Another was a fixed solar panel "box" with four vertical sides, again positioned on top of the robot. For comparison purposes, the total surface area of each of these solar panel configurations was assumed to be equal. The third configuration was a fixed wind turbine on top of the robot. The fourth was a movable wind turbine, free to rotate with the wind such that it always maximized the power generated, no matter which direction the wind blew relative to the robot's direction of travel.

The five coverage patterns generated included a straight rows pattern, a spiral pattern, a curved rows pattern, a sun-following rows pattern, and a random pattern. The random pattern was considered due to the possibility that pattern deviations to examine targets more closely would occur so frequently as to make the pattern appear random in the long run. The straight rows and spiral pattern are fairly self-explanatory. The straight rows pattern was oriented such that the wind direction relative to the robot's orientation produced the optimal wind power generation for the fixed wind turbine. The solar power was also optimal at the start, but due to the motion of the sun, the orientation gradually became non-optimal. The curved rows pattern assumed the robot started in an orientation such that the solar and wind power generated was optimal. The pattern then directed the robot to follow a straight row, but after returning from a round-trip row, to turn just enough such that the new orientation of the robot along the next row was again optimal with respect to the sun, at least at the start of the row. The sun-following rows pattern also assumed the robot started in an optimal orientation, but then continually turned at a rate such that the robot always maintained this optimal orientation, both on outbound and inbound rows. These two patterns generated similar groundtracks, but their differences can be seen below in Figure 1.

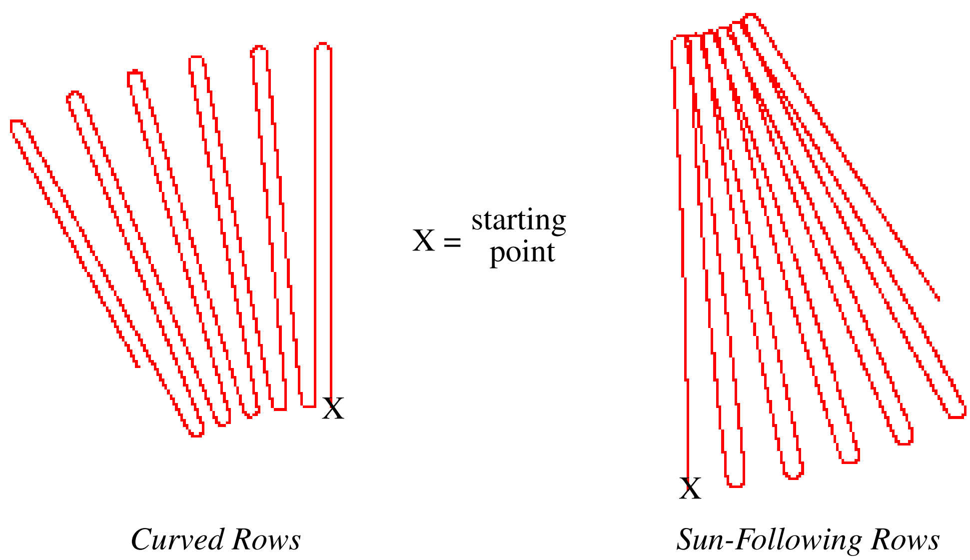

Figure 1: Coverage Pattern Groundtrack Comparisons

Due to the assumptions made, the power consumed, the distance traveled, and the power gained by the rotating wind turbine were the same for all five pattern types. For the non-rotating wind turbine configuration, the power gained was the greatest for the straight rows pattern, due to the assumption that the rows were aligned with the wind direction. Each of the other four types of patterns only generated about 65% of this power when summed over the entire 24 hour period. The two solar panel configurations produced the most solar power when using the sun-following rows pattern, as should be expected. Following the curved rows pattern generated almost this amount of power - 99%. With the solar panel "sail" configuration, the other three patterns generated about 65% of the maximum power generated, while the solar panel "box" generated about 91% of that power. See Figure 2 below.

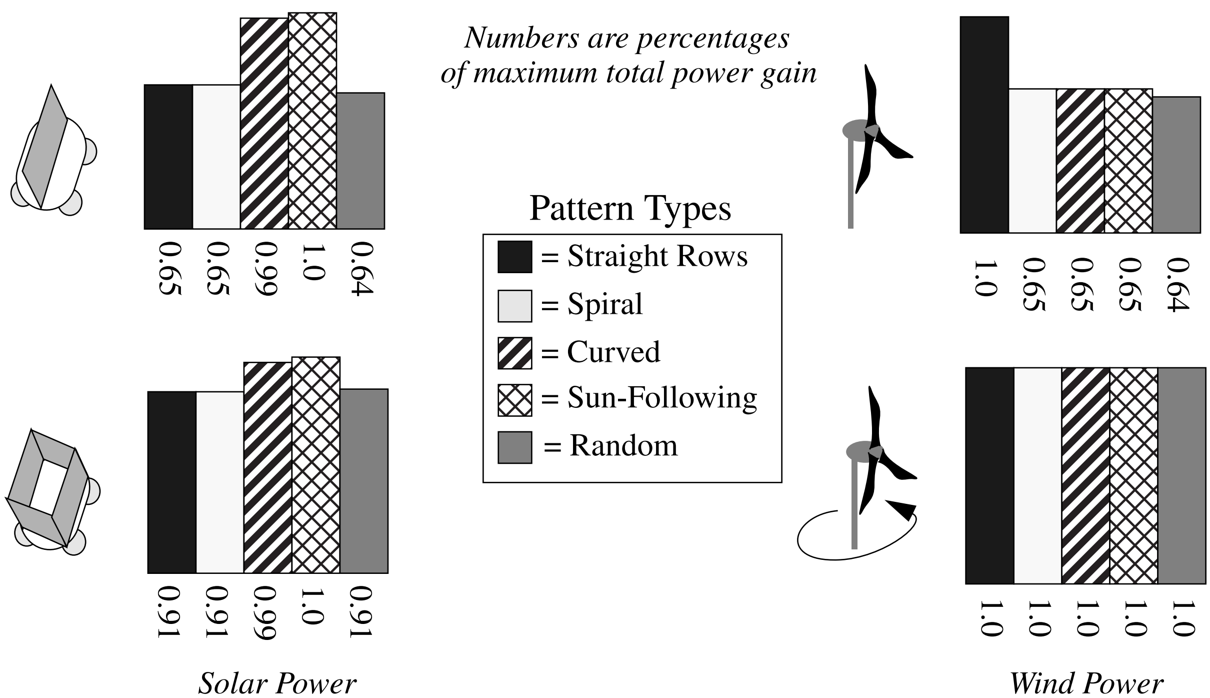

Figure 2: Power Generation

The other two evaluations considered were the percent of area missed, out of a bounding area which encompassed the entire pattern performed, and the percent of area covered more than once, or area overlap. The straight rows and spiral patterns did not miss any area and did not cover any area twice. The curved rows pattern missed 48.3% of the circular area encompassing the pattern. This was due to a large "doughnut hole" in the middle of the pattern, as well as missing area at the outer ends of the rows. 2.4% of the area was covered more than once, due to overlapping at the inner turns of the rows. The sun-following rows pattern missed 19.6% of the bounding area, again due primarily to a hole in the middle of the pattern. Similarly, 23.2% of the area was covered more than once near the inner portions of the rows. This overlap can be seen clearly in Figure 1, at the top of the sun-following rows groundtrack picture. These percentages will vary depending on the length of the rows traveled and the speed of the robot. For the random simulation, the robot missed covering 89.6% of a rectangular bounding box which encompassed all the area the robot did cover. 23.1% of the area was covered more than once. These percentages will also be different every time a random pattern is generated. The comparisons between patterns, however, provided valuable information about the generic differences between coverage pattern types, showing what types of patterns were similar in what respects.

Nomad Tests

The algorithms to generate the straight rows and spiral patterns developed in the earlier simulation work were useful in practice. These two algorithms were modified and implemented to work with the Nomad robot for its Antarctic expedition in the late fall of 1998. A navigation planner software module was written which can generate either a straight rows or a spiral pattern, or can go to a designated waypoint. Various parameters can be set for the straight rows pattern, such as the length of the rows to travel, the separation between rows, the width of the area to cover, the minimum turning radius allowed by the robot at the end of the rows, and the distance from the robot the sensors can reach. Another option allows the user to define the vertices of a convex polygonal area to cover, and the row length will be determined automatically, changing to fit the designated area. For the spiral pattern, the separation between spiral loops, the maximum radius of the spiral, and the direction of travel, either clockwise or counterclockwise, can be set. The starting point of the patterns or a waypoint goal, in global or relative coordinates, can be entered by the user.

The navigation planner maintains state information about the pattern or path plan currently being enacted, takes the robot's current location, and determines the steering angle and speed required for the robot to continue the plan. This steering angle and speed is sent as a command to the robot's navigation system using TCA interprocess communication protocols. The details of the plan to enact is initially sent to the navigation planner by a mission planner software module. The goal is for this mission planner to have more functionality eventually, to be able to mediate between possible plans, as described previously in the technical approach section. Currently, the mission planner only passes through commands from a user interface, using NDDS communication protocols. With this interface, the user can interrupt a patterned search, commanding the robot to go to a waypoint and use its close range sensors on a target object. After the sensor measurements are taken, the robot can be commanded to return to the pattern, continuing until the designated area has been covered.

The navigation and mission planners were tested at the slag heaps near the Monongahela River in Pittsburgh. The available space was large enough for a spiral pattern of approximately 20 meter radius, and a straight rows pattern of 30 by 25 meters. Testing of these patterns allowed many improvements of the path following algorithm used, in addition to the pattern generation itself. Characteristics of the steering ability of Nomad had to be accommodated for in order to keep the robot on the designated path as closely as possible. A pure pursuit path following algorithm was implemented, with varying lookahead distances designed to prevent oscillations around the path and at the same time, enable the robot to return to the path as quickly as possible after a deviation occured. Actually utilizing the pattern algorithms on a real system provided insights not only into how to maintain a given path, but also into the types of deviations which might occur and affect the uncertainties of the path's power generation and consumption evaluations. The differential GPS coordinates of the robot as it pursued the patterns were recorded. The best trials to date, showing how closely the robot followed the patterns, are shown in Figure 3 below. Testing in Antarctica is currently being performed to evaluate how well the coverage patterns are followed, as well as evaluate the robot's locomotion capabilities, power consumption and steering activity, where larger areas and different terrains may affect the performance.

Straight Rows Pattern *Spiral Pattern*

Figure 3: Slag Heaps Testing Results, Pattern Groundtracks

Solar and Earth Visibility Calculations

The simulation described earlier for calculating solar power generation made rather strict and simplistic assumptions about the motion of the sun. Some work has been done in calculating the true visibility over time of the sun and the Earth from the lunar polar regions. Using a program which determines the right ascension and declination of the sun and Moon with respect to the Earth, at any given date and time, these values were converted to the lunar coordinate system. Given the date and time and the latitude and longitude of a location on the Moon, the angle of the sun's and Earth's elevations above the horizon are calculated. Work still needs to be done to convert the information into a direction and orientation with respect to a robot's solar panels or communications antenna. The angles calculated also assumed the Moon is a perfect sphere.

From a position near the lunar south pole, at a latitude of 89.3^{o} S and longitude 255^{o} W, the sun remains above the horizon for an extended period of time. Graphs of the visibility of the sun and the Earth from this location on the Moon are shown below in Figure 4, for the entire year from January 1st to December 31st, 2000. The approximately monthly cyclic variations are due to the Moon's revolution around the Earth, while the longer yearly cycle for the sun is due to the Earth's revolution around the sun. The small relative angles between the Earth-Moon and Earth-sun orbital planes, in combination with the direction of the Moon's rotational axis, are what enable the extended periods of sun visibility.

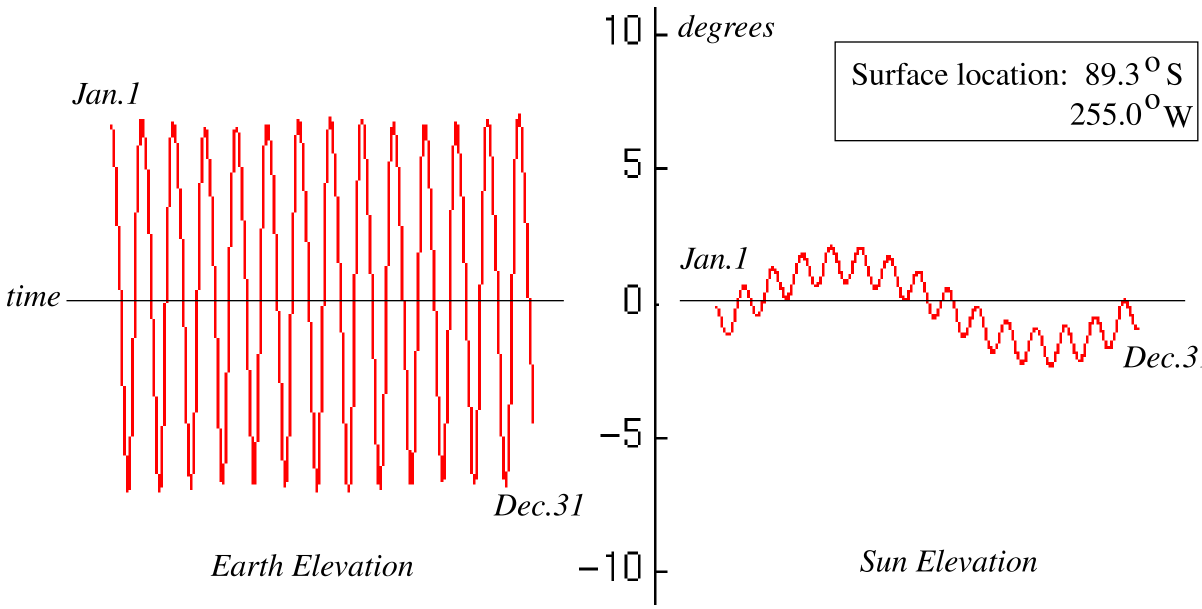

Figure 4: Earth and Sun Elevations Above Lunar Surface

Some calculations of how the terrain affects the visibility of the sun and Earth were also made. A study was made to determine if certain craters near the lunar polar regions could be cold traps. These are areas which are never illuminated by sunlight, maintaining such cold temperatures that any ice in the craters never sublimates. Comparing the elevation angle of the sun over time to the elevation of the crater's walls, both as seen from the center of the crater, determines whether or not the crater is a cold trap. Similarly, the visibility of the Earth from such craters was studied to determine if communication with ground-based operators would be possible [15].

Proposed Research Plan

The proposed research will develop a mission planner which evaluates a set of tasks and plans based on the resources and goals of interest to robotic explorers, primarily power generation, power consumption, area coverage, and sample classification. In addition to the planner development work, actual implementation and testing will be a major component of the thesis work. Several of the issues below are dependent on the particular robotic explorer being used. The primary testbed to be used in this research is Nomad. As discussed in the work to date section, the Nomad rover is a well developed research platform which has been tested extensively in the Atacama Desert in Chile and in Antarctica. A simulation of Nomad will be used extensively for testing the logic of the planner and its components, as well as for evaluating the effectiveness of the planner. As the opportunity arises, tests with the real Nomad will also be performed. Nomad's primary power source is gasoline, but its power consumption can still be tested, and power gain can be simulated. Another testbed could be the proposed "meteorobot" which will have fixed solar panels and possibly a wind turbine. Other mobile robots designed for exploring may also be considered.

The anticipated research agenda is itemized below:

General Research

1. Develop an algorithm based on the orbital parameters of the planetary bodies to calculate the position of the sun, and when relevant, the Earth, as seen from a point on the surface of another planetary body. Three cases will be considered: the Earth, the Moon, and Mars.
2. Merge the terrain map with the sun and Earth position algorithm to determine when the sun or Earth is in line of sight of a given point on the surface.
3. Incorporate *a priori* large-scale terrain data with locally generated maps to create a higher resolution map of the environment.

Power Generation

1. Define the robot configuration(s) to be used, such as solar panels and wind turbine. A standard configuration will be defined at first, with additional configurations added when specific robot platforms are developed.
2. Merge the solar panel configuration with robot pose and sun position information to calculate the solar power which can be generated.
3. Merge the wind turbine configuration with robot pose and wind direction information to calculate the wind power which can be generated.

Power Consumption

1. Develop an algorithm to relate the steering activity to power consumption. This will require locomotion tests to be performed on the specific robot used.
2. Determine the power and time costs of various sensor measurements.
3. Relate each path type to the steering activity involved. The path types to be considered are: straight rows, spiral, sun-following, and other coverage patterns which may be developed.
4. Incorporate terrain features into the power consumption calculation. For example, going uphill requires more power, and traveling on snow may require more power than traveling on ice.

Uncertainty

1. Determine how to handle uncertainty in making evaluations and ranking tasks and plans.
2. Develop a measure for the uncertainty of power generation and area coverage evaluations, based on the changes in robot orientation due to terrain features. The uncertainty may vary for different paths, so consider all coverage pattern types.
3. Develop a measure for the uncertainty of power consumption evaluations, based on the changes in steering activity which may occur as a result of terrain features. Again, this may differ for various coverage pattern types.

Tasks

1. Develop the algorithm for a sun-following coverage pattern. Also consider other possible coverage patterns.
2. Define the steps involved with various sensor measurements or other non-coverage pattern tasks.
3. Develop a maneuver planner to move the robot into a certain orientation at a certain position. Locomotion tests will need to be performed for this.
4. Incorporate the terrain map with the path and maneuver planners, considering only how best to avoid obstacles and cover the terrain.

Rankings

1. Develop evaluation methods for goals such as area coverage and sample classification, including any uncertainty involved.
2. Coordinate the evaluation methods and priority selections to generate appropriate rankings.
3. Develop algorithms or heuristics for relating the priorities to environmental factors and evolving mission stages

Evaluation of Thesis Research

The utility and effectiveness of this research will be evaluated in several ways. The mission planner will choose certain tasks over other, less optimal tasks. Calculating just how much better the chosen tasks are will show the benefit of having such a planner. The total power generated and consumed during the enactment of the chosen task will be compared to the power generation and consumption of alternate tasks. Another evaluation uses a predefined mission of covering a certain area and classifying any significant rocks in the vicinity, with a given terrain and random target locations. The total power generated and consumed, and the time required to complete the mission can be calculated for two cases. In one case, the task evaluation method is used to select the best tasks as the mission progresses. In the second case, a single preselected coverage pattern is performed, with deviations to investigate when target objects come within sensor range. In this second case, the power generated during the coverage pattern is likely to be insufficient, requiring the robot to pause in a certain orientation to generate more power reserves before continuing. This will reduce the amount of productive time during the mission, which is another number to be used in evaluation. The accomplishment of mission goals can also be calculated, such as the amount of area actually covered and the number of targets classified correctly. The evaluations will be done both in simulation, and when possible, with actual hardware. Secondary to these calculations, the implementation of the planner can be evaluated by noting how accurately the robot follows the given tasks and plans.

Schedule

The expected schedule in which the above work will be completed is shown in the table below. The numbers refer to the listing of tasks in the previous proposed research plan section.

Time Period	Task
January - May 1999	*General Research*: orbital parameters algorithm (1), merge terrain map with orbital parameters (2) *Power Generation*: standard configuration (1), merge solar configuration with pose and orbital parameters (2) *Tasks*: sun-following algorithm (1), define task steps (2)
June - October 1999	*General Research*: merge *a priori* maps with local maps (3) *Power Consumption*: relate steering activity to consumption (1), determine sensor costs (2) *Uncertainty*: determine how to handle uncertainty (1) *Tasks*: maneuver planner (3), incorporate terrain map (4) *Rankings*: develop goal evaluation methods (1)
November - December 1999	Proposed testing in Antarctica
January - May 2000	*Power Generation*: merge wind configuration with pose and environment (3) *Power Consumption*: relate path types to steering activity (3), incorporate terrain (4) *Uncertainty*: develop uncertainty for power generation (2), develop uncertainty for power consumption (3) *Rankings*: coordinate evaluations and priorities (2), algorithms/heuristics for priorities (3)
June - August 2000	Proposed testing in slag heaps, overall planner evaluations
September - December 2000	Final write-up
December 2000	Defend thesis

Table 2: Research Schedule

Significance

Three facets of this research are of primary significance. One, this work will provide a means for choosing tasks and plans which generate the most power. This ability will be critical for future planetary exploration by robotic vehicles, which depend on extremely limited resources.

Two, this research will produce a planner which evaluates solar power generation for coverage patterns. More generally, tasks can be evaluated based on changes in resources or goals which are predictably, yet continually and nonlinearly changing throughout the duration of a single task. Combining a solar orbital parameters algorithm with an onboard planner will enable solar resources to be evaluated by the robot. Other resources vary depending on the environment, while the goals also vary depending on the current stage of the mission.

Three, this research will produce an implementation of a complete mission planner for a remote surface robotic explorer with multiple tasks, capable of working with no human interaction from deployment to mission completion. The planner will be demonstrated in simulation, or else added on to an existing robot platform, with navigation, sensors and real-time control already developed.

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