Automated Surface Mission Planning Considering Terrain, Shadows, Resources and Time

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Abstract

This paper summarizes initial work on a planetary rover planning domain where long-distance traverse, large-scale terrain, changing line-of-sight geometry, finite resources and time strongly affect the strategy for achieving mission objectives. In this domain, because path planning, activity scheduling and resource usage are closely coupled, they must be considered simultaneously. We introduce a preliminary automated planner that combines planetary and rover modeling with a novel search algorithm to produce coarse navigational and activity plans for long-distance rover traverses. Results from simulation illustrate the utility of the approach, and pave the way for field experiments in planetary analog terrain. Finally, we present our plans for future research and development in the domain.

1 Introduction

Future missions will demand rovers capable of exploring canyons, valleys and polar regions in search of water, ice and for signs of life. In the coming decades, the trend will be to explore ever more difficult terrain where science data tends to be the richest. The terrain capabilities of future robotic vehicles will permit confident mobility through rock fields and other hazards, enabling multi-kilometer daily excursions and access to a large percentage of a planet's surface (e.g. [7]). Example destinations might include Mars' Valles Marineris and the moon's South Pole Aitken Basin. Such operations will be limited by insurmountable large-scale terrain, dynamic occlusion of sunlight and communications, and finite resources and time. Scheduling rover activities, for example stationary solar array charging, must not only consider conflicts with other activities, but also the position and absolute time at which the activity occurs as functions of path. Meanwhile, path planning must consider how the choice of path impacts sun and communications access and how path-dependent timing of resource collection and use interacts with resource constraints (e.g. battery minimum and maximum state-of-charge). Long-range forecasting of these interactions may sometimes mean the difference between significant losses and mission success. Limited *a priori* knowledge of terrain, rover performance and changing goals will further complicate plan creation in these scenarios.

In response to this emerging need, we have begun work on automated mission planning that reasons about the interplay between mission goals, planetary motion and terrain, and operational constraints, and that quickly re-plans as terrain, state and goal knowledge evolves. We submit that this planning capability is critical to the success of missions where terrain, lighting and limited resources force a tight coupling between path planning and activity scheduling, and would serve the needs of both robotic and human exploration in the Solar System.

Our planner is called TEMPEST (TEmporal Mission Planner for the Exploration of Shadowed Terrain). TEMPEST resides as a component of the upper, deliberative layer of an autonomous control architecture, but displays qualities that enable quick replanning that provides response to new data characteristic of reactive systems. It operates on mission objective specifications (e.g. science survey target locations, required durations at each site), planetary models (e.g. ephemerides, digital terrain models), and rover models (e.g. power requirements, energy collection, data and communications constraints) as a basis for analyzing the effects of path and activities on mission outcome (see Figure 1). The dynamic nature of the domain, deriving primarily from planetary and rover motion and their effects on lighting and communications, requires an approach that emphasizes time as a plan parameter. In its current instantiation, TEMPEST populates a spatio-temporal grid with terrain and line-of-sight data, and performs a search on the grid to determine a mission sequence that satisfies mission and operational constraints while optimizing a parameter (e.g. distance traveled). TEMPEST generates a plan consisting of path waypoints defined by spatial coordinates and times, and associates activities with waypoints along the traverse (e.g. orient the solar array to a particular attitude and charge the battery for 20 minutes). The resulting plan is then delivered to a middle, executive architecture layer for execution.

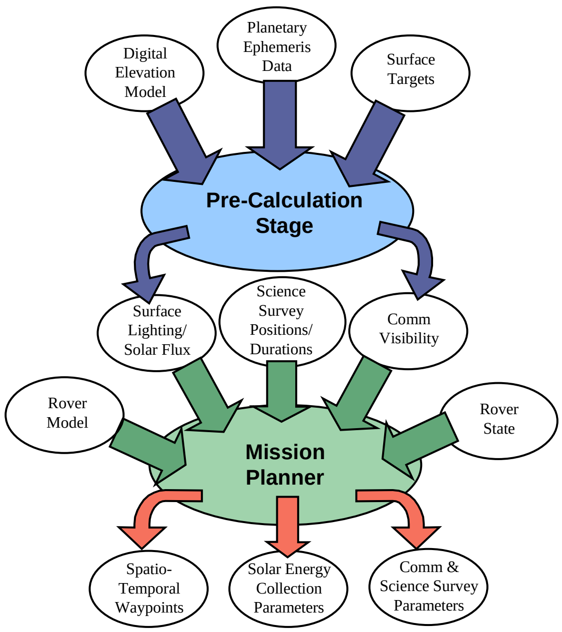

Figure 1: TEMPEST pre-calculates maps encoding line-of-sight visibility, and utilizes rover models and mission target specifications as a basis for search.

TEMPEST simultaneously derives a path plan and a framework for activity scheduling. Relevant events are considered in the context of the rover path, resulting in plans that are integrated from the outset. For example, the choice of path impacts energy used for locomotion (through distance, speed and slope), when solar energy can be gathered (through shadowing and solar array orientation), and consequently defines when recharging must occur.

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

1.1 Future Motivation

We introduce the moon's South Pole Aitken Basin as a probable target for future rovers whose challenging environment motivates this research. Orbital missions over the past several years indicate a high probability of water ice trapped in permanently shadowed regions of the lunar poles, and hence present a strong scientific motivation for surface exploration (e.g. [5]). During summer months at the pole, the sun rises no higher than 1.5°, and appears to skim the complete horizon over the course of the moon's 29.5-day lunar month [6]. Meanwhile, a combination of axial tilt and orbital eccentricity cause the Earth to inscribe a tilted elliptical path that rises to 6.7° above the horizon at its high point and falls to 6.7° below the horizon roughly two weeks later. The south pole region is known for its rough terrain; in conjunction with such low sun and Earth elevation angles, terrain causes substantial sun and communications shadowing. Surface shadow patterns change continually with the moon's rotation and progress of the Earth/moon system about the sun.

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

We submit that less extreme missions would also benefit from this form of integrated mission planning. For example, a planner could contribute to a near-term Mars rover mission by instructing a rover to terminate its daily activity schedule on a slope in a favorable orientation, thereby improving morning sun incidence on its solar array. Imaging of a particular rock might be timed and placed to ensure direct sunlight and to avoid rover shadowing of the scene.

2 Related Work

Significant research and development efforts have resulted in effective strategies for rover path planning to enable autonomous travel in natural terrain. One example is RoverBug [8], which utilizes local tangent graphs to construct minimum-distance paths about obstacles detected by rover sensors with limited range and fields-of-view. Using a dual strategy of "motion-to-goal" and "boundary following", the algorithm has successfully demonstrated path planning and execution aboard the JPL Rocky 7 Mars rover prototype. A CMU path planner [12], also produced with Mars rover navigation in mind, is based upon the D* algorithm [14][15][16]. Using a grid-based approach, D* uses sensor information to populate cells with traversability data, and plans paths that avoid hazards and that are distance-optimal under current world knowledge. This scheme has been successfully demonstrated on a CMU ATRV robot [12], and will be demonstrated in modified form on the CMU Hyperion rover in July 2001 [18]. Each path planner minimizes distance in producing paths, but ignores other potential factors (e.g. slope, sun position) and associated costs and benefits over the traverse. Both path planners are designed to permit autonomous navigation on the scale of 100 m, in accordance with near-future Mars rover requirements. Neither addresses an anticipated requirement for autonomous travel on the scale of 10's or 100's of km.

In the arena of grid search applied to path planning, the D* (Dynamic A*) algorithm [14],[15],[16] was developed to balance the rigor of deliberative planning with the rapid response of reactive behavior. Like A*, D* operates on a map of cost values and finds the lowest cost path from the start to the goal. Employed on a vehicle in unknown terrain, D* enables incremental changes to initial plan as new information is collected. As cost values in the map are modified, D* computes a new optimal path from the vehicle's current location to the goal. D* uses incremental graph theory techniques to continually "repair" the path and efficiently produce a new optimal path to the goal, based on all information learned and aggregated to that point. For large maps, D* is hundreds of times faster than re-planning from scratch using A*, yet it produces the same results. Unfortunately, D* has its limitations. As formulated, the algorithm does not have mechanisms for dealing with the proliferation of search states that typically arise from high-dimensional, constrained path finding problems. For example, in addition to minimizing the length of a traverse, it may be important to constrain the feasible paths by terrain difficulty, driving time, energy expended, risk of accident, sensor coverage of areas of interest, and time spent out of communication. Each constraint increases the size and dimensionality of the search space and thus the time and memory required to find a path. Without careful management of the search, even small problems can become intractable.

Automated activity planning and scheduling software has been successfully deployed on spacecraft and prototype planetary rovers, including Remote Agent [2] and ASPEN [3]. In particular, the ASPEN system and the derivative CASPER system were separately integrated onto the JPL Rocky 7 rover and used to produce coordinated activity schedules based on science and engineering team requests. The activity planners enabled plan repair and reformulation in response to changing goals and other unexpected events. Rover activity scheduling experiments considered resources and environment effects (e.g. day/night cycle, sun angle), but demonstrated only loose coupling to path planning, focusing primarily on conflict resolution through event rescheduling or reordering.

Shillcut [11] analyzes how various rover terrain coverage patterns affect incoming sunlight, and provides motivation for planning under such considerations.

3 Method

3.1 Environment Modeling

TEMPEST combines planetary models with models of rover performance and operational constraints to form a basis for path and time search. TEMPEST utilizes digital elevation data sets to encode terrain in the area of operations, and pre-calculates slope and aspect using this data. Digital elevation models are becoming more readily available on a global scale and at ever-increasing resolution for both Mars [13] and the moon [10],[4]. It is expected that long-distance surface investigations would be preceded by detailed orbital surveys from which digital elevation data could be derived, as in [9].

Surface lighting, communications visibility and surface-to-surface visibility are all fundamentally determined by line-of-sight geometry. TEMPEST employs a ray-tracing algorithm to determine line-of-sight visibility from the sun to cells for lighting and shadows, from the Earth to cells for communications and cell-to-cell to determine visibility from the rover to surrounding terrain. Elevation and slope data are de-projected from maps to the planetary sphere or ellipsoid to account for horizon effects. Planetary motion is modeled using JPL CSPICE software [1]. For line-of-sight data that are time dependent (e.g. sunlight), the software pre-calculates exposure for the complete map for each time slice. The result essentially amounts to a movie encoding the angle of incidence of the source on the terrain for each time step. In addition to calculating line-of-sight, TEMPEST uses a simplified model to calculate available solar flux to account for solar distance and gross atmospheric effects, if applicable.

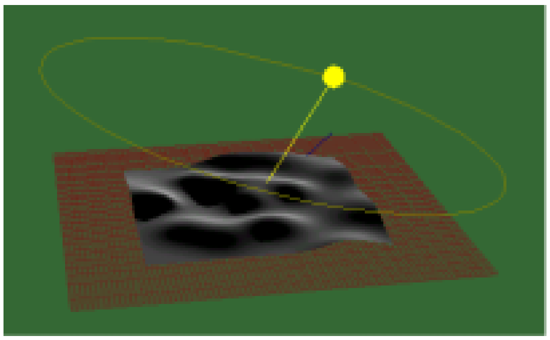

Figure 2: TEMPEST combines elevation and ephemeris data to predict sunlight and shadowing on terrain

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

3.2 Path Search

TEMPEST finds shortest paths that are constrained by the available sunlight and the energy capacity of the rover's battery. The planner represents and reasons about two spatial dimensions, time, and energy level. To manage the high dimensionality of this space, TEMPEST uses the Incremental Search Engine (ISE) [17]. Like D*, ISE is a heuristic search algorithm that incrementally re-plans optimal paths, but ISE also efficiently manages constraints on the feasible set of solutions. ISE plans an initial path given all known information about the world that satisfies the constraints and is optimal. As the vehicle follows the path generated by ISE, it discovers new information with its sensors. ISE stores this new information and re-plans a new path, in real time, that is both feasible and optimal. This process repeats until the vehicle reaches the goal or determines that it cannot.

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

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

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

3.3 Mission Execution

The TEMPEST mission execution procedure is based upon an initial, simplified approach created for the Hyperion rover field experiments [18]. TEMPEST currently runs off-board Hyperion, but future versions will be rover-based. Initial TEMPEST planning happens off-line, to enable an in-depth review of results by rover operators. During a rover traverse, new plans can be generated at the request of human operators or by the rover itself. During pre-mission planning, operators specify a series of sparsely-distributed waypoints representing intermediate targets for science, or sub-goals directing the rover on a desired general path or steering the rover away from known terrain hazards. TEMPEST assumes the traverse must occur within the span of time represented by the pre-calculated lighting data. It searches for the optimal departure time using a metric of battery energy required at the beginning of the traverse to achieve a desired battery level at the end of the traverse. TEMPEST plans the full, multi-leg traverse at even intervals across the available time span, in each case determining the required initial energy. Those paths that exceed the rover's current load, or that violate the constraints for minimum and maximum battery state-of-charge, are ignored in favor of paths predicted to be executable. The optimal departure time requires the minimum energy to meet all traverse specifications. A nominal first plan is stored for the beginning of execution.

TEMPEST path plans comprise a sequence of spatio-temporal waypoints whose spatial interval matches the grid spacing of the digital elevation model, and whose temporal resolution depends on grid spacing and average rover speed. TEMPEST assembles a coarse activity schedule by associating activities with waypoints (e.g. perform stationary charging at waypoint 5). After TEMPEST generates a traverse plan, it passes the waypoints and activity flags to a mission executive that supplies goal information to the local navigator, distributes parameters for events (e.g. charge duration, sun azimuth/elevation), monitors mission execution and requests re-plans as necessary. The mission executive translates plan waypoints into goal regions that enable the rover to maintain a constant heading and that prevent complications when goals are co-located with terrain hazards. Nominally, the local navigator is able to direct the rover autonomously from its position to the region, and reports a completion of the subgoal with a summary of its current state information. The mission executive determines whether the actual state is within tolerance of the projected state for that waypoint. If within tolerance, the mission executive supplies the local navigator with the next waypoint. An out-of-tolerance waypoint triggers a re-plan request message that is sent to TEMPEST with the current rover state. Alternately, if the navigator reports that no paths can be found to the waypoint, it is assumed the map cell cannot be crossed. The map cell is marked with a very high cost, and again a re-plan request is sent to TEMPEST.

Re-planning occurs on the search data structure initiated in the original plan, and updated with each re-plan. Re-planning is performed incrementally based on new initial conditions and updated path cost information, and is significantly faster than the initial planning run.

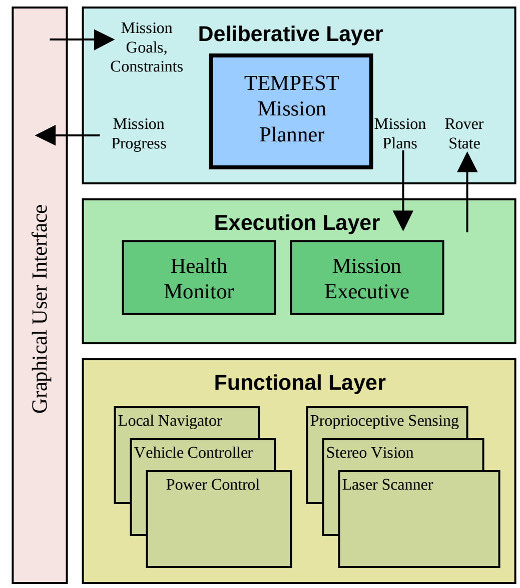

Figure 3: TEMPEST interacts with the mission executive and rover operators to re-plan as goals change or the rover state differs significantly from projections.

TEMPEST provides plans whose resolution is limited by the terrain data available, and by computational speed and memory limitations of the planner's host platform. Uncertainties in rover navigational capability and in rover performance further complicate long-distance and long-duration planning. Consequently, TEMPEST must operate in conjunction with local path planning and obstacle avoidance software that enables autonomous travel between Furthermore, TEMPEST provides only a framework for activity planning structured around activities whose placement is tied closely with the selected path. Future versions may work closely with activity planning and scheduling software that is optimized to resolve activity conflicts, planning at the greatest level of detail in the short distance and the near term.

4 Preliminary Results

Early off-line results from TEMPEST indicate its utility for mission planning. Initial planning runs were conducted on synthetic digital terrain artificially placed at the same location where TEMPEST field experiments will happen in July 2001 (see Future Work). The test terrain is more pronounced than that expected in the test site, and coupled with the low-elevation Arctic sun, casts substantial shadows. The test rover model mimics the Hyperion rover performance and configuration, including mass, average speed, projected power draw and solar array area. Like Hyperion, the rover model uses a non-steerable, nearly vertically-oriented solar array that

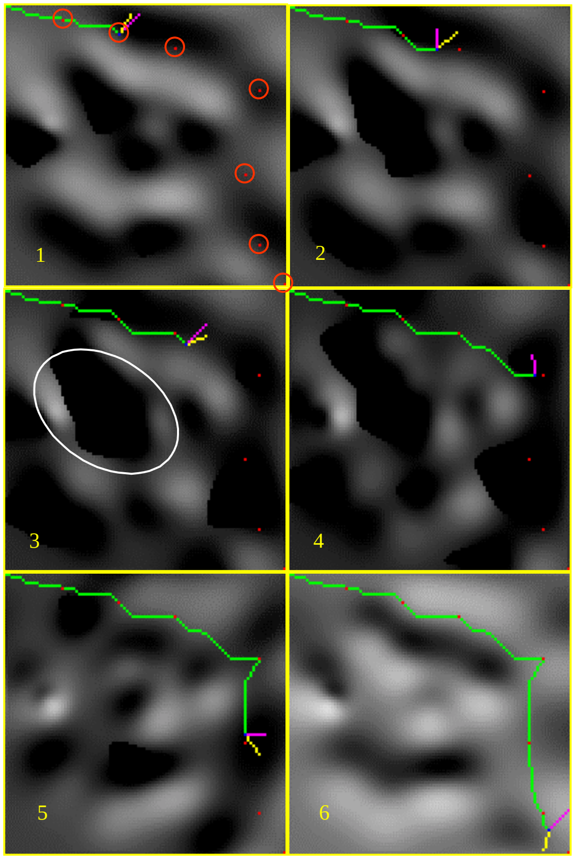

Figure 4: A traverse planned by TEMPEST

faces to the left of the forward driving direction. A fixed solar array reduces mechanical complexity and mass, but couples solar energy collection to the choice of path.

Initial experiments tasked TEMPEST with planning paths from one corner to the opposite corner of a 100x100 cell grid representing a 10x10 km area, depicted in Figure 4 (see also Figure 2 for an aerial view). TEMPEST received a series of intermediate targets, used as guides to narrow the search space. TEMPEST plans considered terrain slope, rover speed, locomotion power, sun position, and solar energy collection. However, TEMPEST was not instructed explicitly to avoid shadows or steep slopes. Plans simply maintain adequate battery levels throughout the traverse and terminate at a user-specified state-of-charge, while minimizing traverse distance.

The sequence of frames in Figure 4 illustrates a specific example. The greyscale background encodes the level of incident sunlight on each map cell, where only a value of zero indicates the cell is in shadow. Dark cells are not necessarily shadowed, but lighted and at low local sun angle. Time advances with increasing frame number, spanning a total of over 16 hours. Planning from the start position in the upper left corner to the final goal position in the lower right, TEMPEST received six intermediate waypoints, shown as red points and circled in frame 1. The green trail represents the rover path. The yellow and purple lines emerging from the instantaneous rover position indicate the pointing direction to the sun and the solar panel normal vector, respectively. Note that the solar panel vector remains perpendicular to the rover path (to the left of forward) and that the sun vector tends to point opposite the direction of shadows cast by surrounding terrain. The sun vector disappears if the rover enters shadow during its traverse.

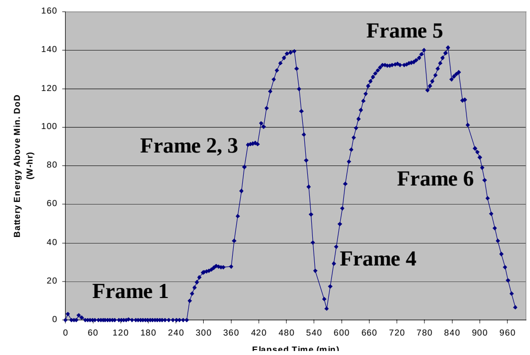

Figure 5: Min. Energy Required Over Path

One should note some salient features of the plan selected by TEMPEST. To assist, a plot of minimum battery energy required to achieve the goal conditions from anywhere along the traverse is included in Figure 5. Note first that there are two obvious routes following low level terrain from upper left to lower right, seen most clearly under the shadows of frame 1. Planning runs attempting to use the lower route all failed due to a substantial shadow that blocks the rover path, circled in frame 3. In frame 1, the solar array normal and sun vectors are nearly coincident. This power-rich situation is reflected in the battery level plot, which indicates that even with minimum energy, the rover can proceed on its course. Solar energy continues to be abundant in frames 2 and 3 as the rover's course gradually turns. The rover path follows on the edge of dark terrain, but avoids the slopes to its right. At this stage the battery level plot indicates a steady increase in required energy, in preparation for an excursion into shadow to reach the fourth target in frame 4. Note that the path takes a direct line in and out of shadow, apparently to minimize the time without solar exposure. The shadow entry causes a major reduction in battery level. In frames 5 and 6, the rover path remains at a fixed heading and then turns away from the sun, causing the sun/solar array angle to gradually increase.

To compensate for coming energy difficulties, the plan maintains sun angles for battery charging. However, to reach the end of the traverse, the sun must shine on the inactive face of the array, preventing recharge and depleting the battery level to its minimum.

This example illustrates TEMPEST's ability to reason through complicated mission planning situations. Despite direct coupling of solar energy collection and path heading, and frequent conflict between the goal of minimum distance and maintaining battery charge, TEMPEST finds a route that satisfies all mission constraints.

5 Future Work

TEMPEST is scheduled for field demonstration in July 2001 as part of the NASA Sun-Synchronous Navigation project [18]. The project demonstration seeks to prove a concept for planetary polar exploration in which a solar-powered rover performs its mission on a continual basis by maintaining a path that is synchronized with planetary rotation. TEMPEST will plan routes through planetary analog terrain on Devon Island in the Canadian arctic, taking advantage of 24-hour sun, while avoiding the long shadows associated with low sun elevation angles. The demonstration goal is to operate continuously for 24 hours, entirely through remote and autonomous operation, returning to the start position after an extended traverse. The rover is very power-limited and will rely heavily upon intelligent use of solar energy collection. Hyperion's fixed-orientation solar array will challenge TEMPEST by forcing a strong coupling between route, timing and solar energy collection. Experiments will begin to quantify the effectiveness of our approach for planetary rover mission planning and execution, and will identify strengths and shortcomings. We hope to determine whether our approach is adequate despite terrain and rover performance uncertainties, and whether replanning and model calibration are sufficient for recovery from early false predictions.

Following the field experiment, we have identified several potential directions for future work:

1. Planning under uncertainty: Uncertainty in *a priori* data, rover performance and rover position will play a significant role in planning extended planetary missions. Modeling these sources of uncertainty and considering their effect on mission outcome may enhance planning effectiveness, and will enable probability-of-success studies.

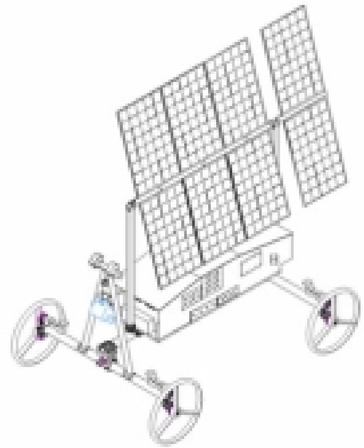

Figure 6: Hyperion will execute routes generated by TEMPEST

2. Contingency planning: Inventing a practical scheme for contingency planning that considers eventualities both inside and outside the expected range of uncertainty might substantially improve an autonomous vehicle's robustness to failures.

3. Planner adaptation: Machine learning algorithms dedicated to collecting data on rover performance relative to projections might aid in calibrating the planner as the mission progresses.

4. Planning in pre-flight analysis and design: The effect of solar array size and degrees of freedom, battery capacity, rover speed and other design factors could be simulated using the TEMPEST framework. We will investigate the utility of TEMPEST in rover design trade studies and surface mission design.

6 Conclusion

TEMPEST demonstrates a preliminary capability for combining path planning, activity scheduling and resource usage applied to planetary surface exploration. Simultaneous consideration of these factors will become critical in scenarios where extreme terrain, dynamic lighting and communications line-of-sight, and limited resources severely restrict strategies for satisfying mission objectives. TEMPEST combines planetary and operational modeling with a heuristic search algorithm to enable optimization of a mission variable subject to one or more mission constraints. Furthermore, TEMPEST is tailored for quick re-planning in response to a changing environment and mission goals. Early demonstrations confirm the utility of our approach in simulated environments. Follow-on work will move TEMPEST from the laboratory to a planetary analog environment for field testing, and will further enhance the planner's capabilities to operate effectively despite uncertainty.

7 Acknowledgements

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