Power-Constrained Path Planning for Planetary Rovers
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Motivation
Future missions to the other planets will require planetary rovers to navigate shadowed terrain and temperature extremes due to the lack of atmosphere. Regardless of whether the rover is autonomous or teleoperated, an algorithm is needed to plan traverses through inhospitable temperatures that preserve battery life. Previous work in this area, such as Paul Tompkins’ TEMPEST planner, posed a similar question but did not address thermal constraints.

Consider the situation where the rover must travel in a direction such that the sun is not incident with the solar panel. To recharge its battery, the rover can either turn to face the sun and wait, or drive in a continuous zigzag, alternating between facing the sun and advancing in the goal direction. A preliminary mathematical analysis gives the function

\[ t = \frac{1}{\cos \theta} \left( 1 + \frac{P_{\text{drive}}}{P_{\text{solar}} - P_{\text{drive}}} \right) \]

where \( \theta \) is the angle of zigzag, \( P_{\text{drive}} \) is motor power consumption, \( P_{\text{solar}} \) is the solar recharge power, and \( t \) is the time needed to recharge. This function has a minimum at a nonzero angle, suggesting that the zigzag is an optimal strategy.

Thermal Model
Given internal motor \( p_{\text{in}} \) (Watts), power due to solar heat on the radiator \( p_{\text{solar}} \) (Watts), and current radiator temperature \( T_{\text{cur}} \) (Kelvin), net power can be found from Stefan’s law using radiator area \( A \), radiator material emissivity \( \epsilon \), and the Stefan-Boltzmann constant \( \sigma \):

\[ p_{\text{net}} = \sigma AT_{\text{cur}}^4 - (p_{\text{in}} + p_{\text{solar}}) \]

The definition of heat capacity gives instantaneous change in temperature \( \Delta T \) from \( p_{\text{net}}, \Delta T \):

\[ \Delta T = \frac{p_{\text{net}}\Delta t}{C} \]

Finite element analysis approximates the transient temperature response over a fixed time interval.

Graph Construction
A map of the world is discretized according to a 5-10m/cell resolution. Euler angles representing the sun’s rays vary across time. This data is kept in a lookup table and consulted throughout the search. A predefined set of rover trajectories to different \( x, y \) positions and headings is copied over the world grid to construct a lattice. Each node in the grid represents a 4D state: \( (x, y, \theta, t) \).

Graph Search
\( A^* \) is used to find to find a least-cost, constrained path from start to goal. The planner minimizes one of three cost functions: path length, time, or energy. There is no cost function for temperature because the model is state-dependent. Instead, the temperature at each state is tracked during search, and the change in temperature is calculated for each newly expanded state. Time or length can be used as a heuristic. With the correct scale factor, time is an admissible heuristic for energy.

Future Work
The thermodynamic model presented is an idealized approximation which disregards several heat sources, including leakage due to heated regolith. The model for motor power consumption while turning/skidding steering could be refined. To extend this research from proof of concept to an operational planner, the runtime of the search could be improved by utilizing graph pruning techniques.

References

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