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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

$$t = \frac{1}{\cos\theta}\left(1 + \frac{p_{drive} - \sin\theta p_{solar}}{p_{solar} - p_{hotel}}\right)$$

where θ is the angle of zigzag, p_{drive} is motor power consumption, p_{solar} is the solar recharge power, p_{hotel} is the constant power cost due to electronics, 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.

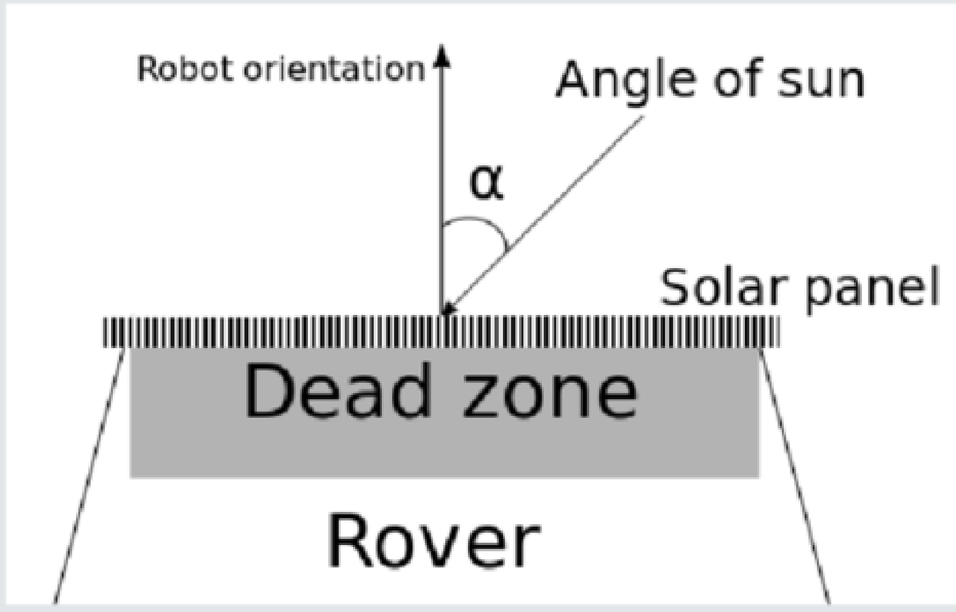
Graph Construction

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, θ, 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.

Energy Model



For area of the solar panel A, efficiency factor η and angle between the sun's rays and the panel normal α,

$$p_{solar} = \eta \cos\alpha A$$

If the angle of the sun is incident to the "dead zone" pictured in the above bird's eye illustration of the rover, $p_{solar} = 0$. The rover's internal power is the sum of power drawn by the motors and the hotel cost:

$$p_{int} = p_{hotel} + \frac{umgv}{n_g n_m}, \; p_{net} = p_{int} - p_{solar}$$

where m is mass, g is gravity, v is velocity, and u, n_g and n_m are determined by motor efficiency.

Thermal Model

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

$$p_{net} = \sigma A \epsilon T_{cur}^4 - (p_{in} + p_{solar})$$

The definition of heat capacity gives instantaneous change in temperature ΔT from $p_{net}, \Delta t$:

$$\Delta T = p_{net}\Delta t / C$$

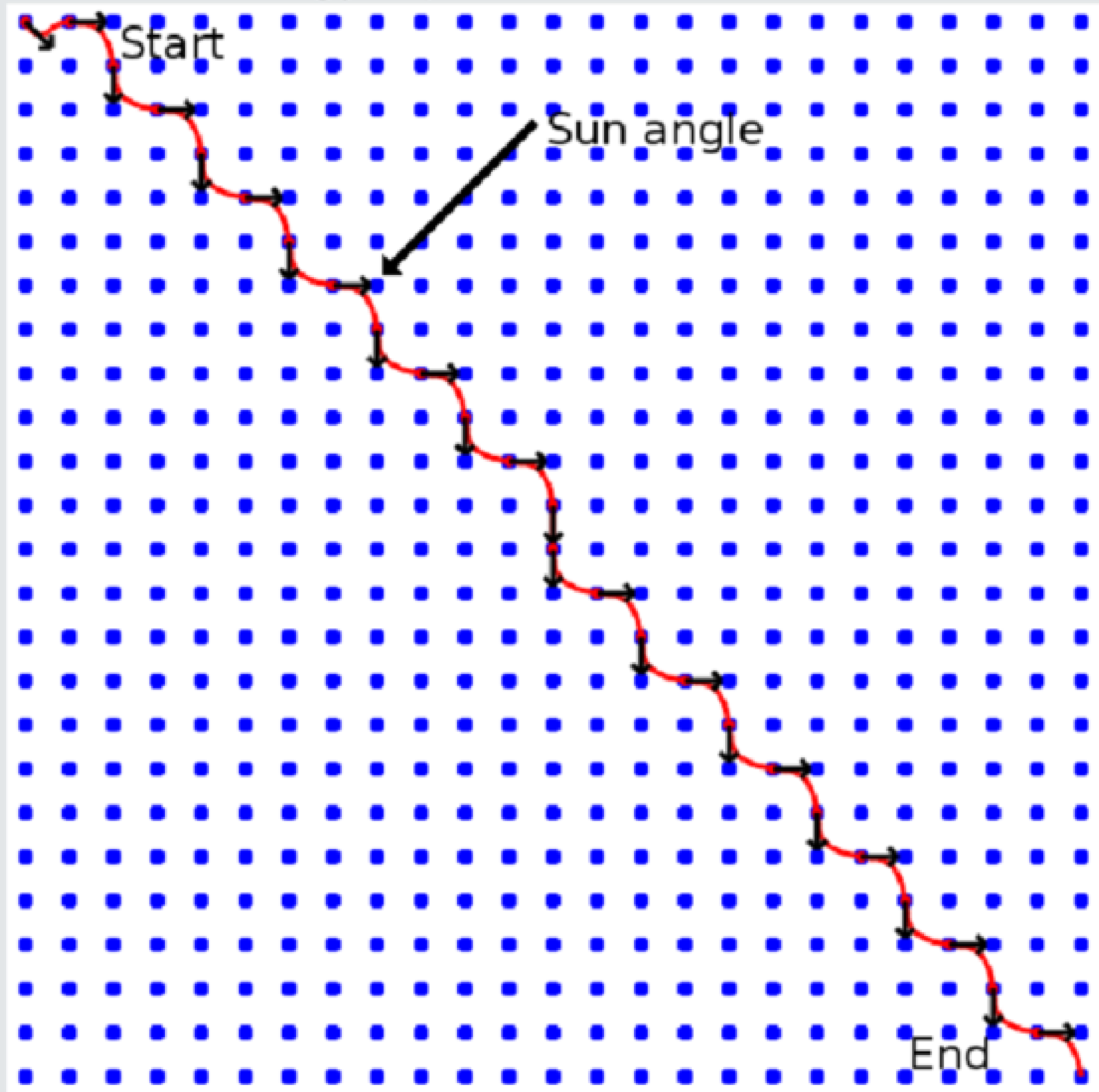
Finite element analysis approximates the transient temperature response over a fixed time interval.

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/skid 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.

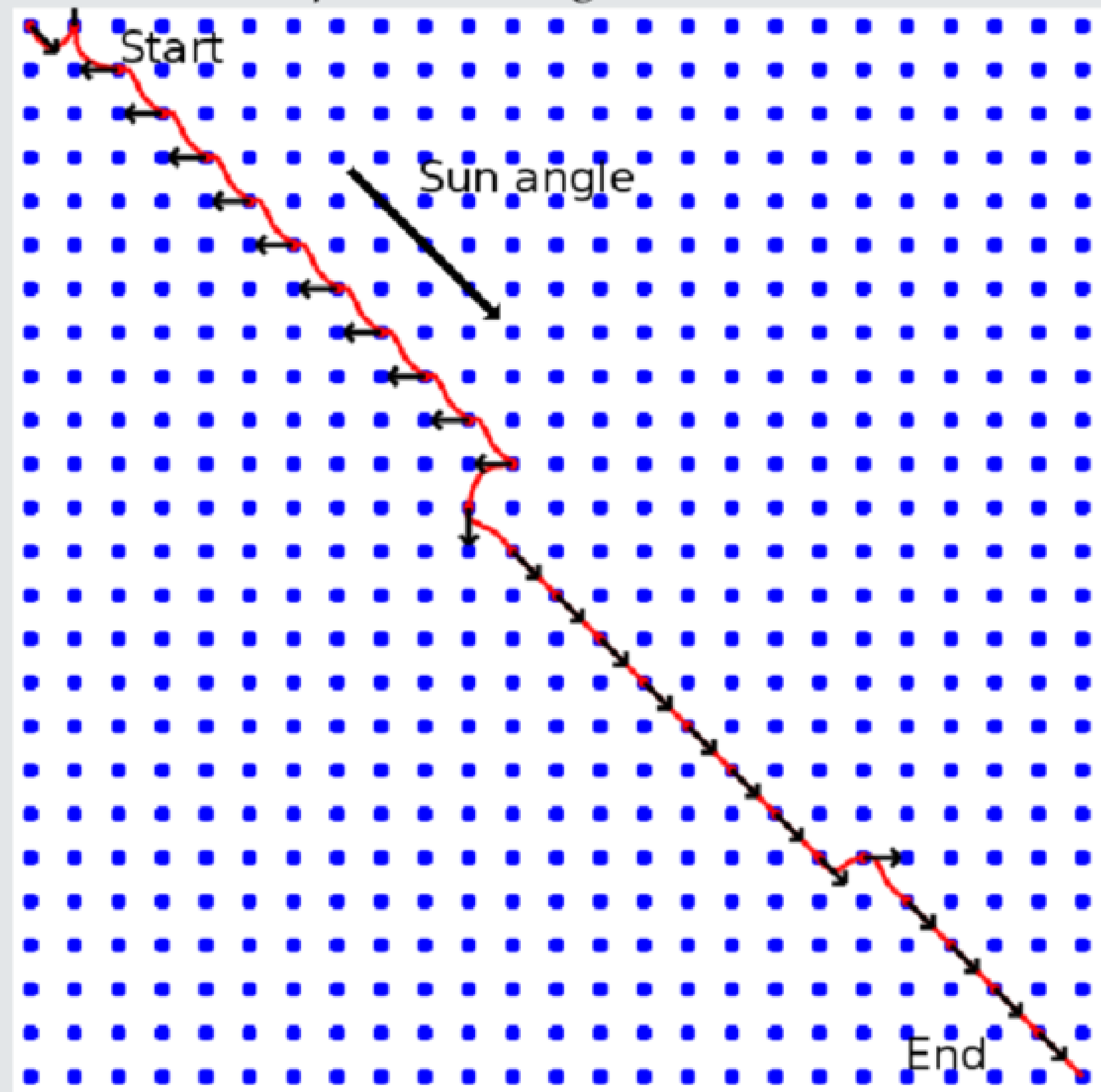
Results

Minimize energy expended



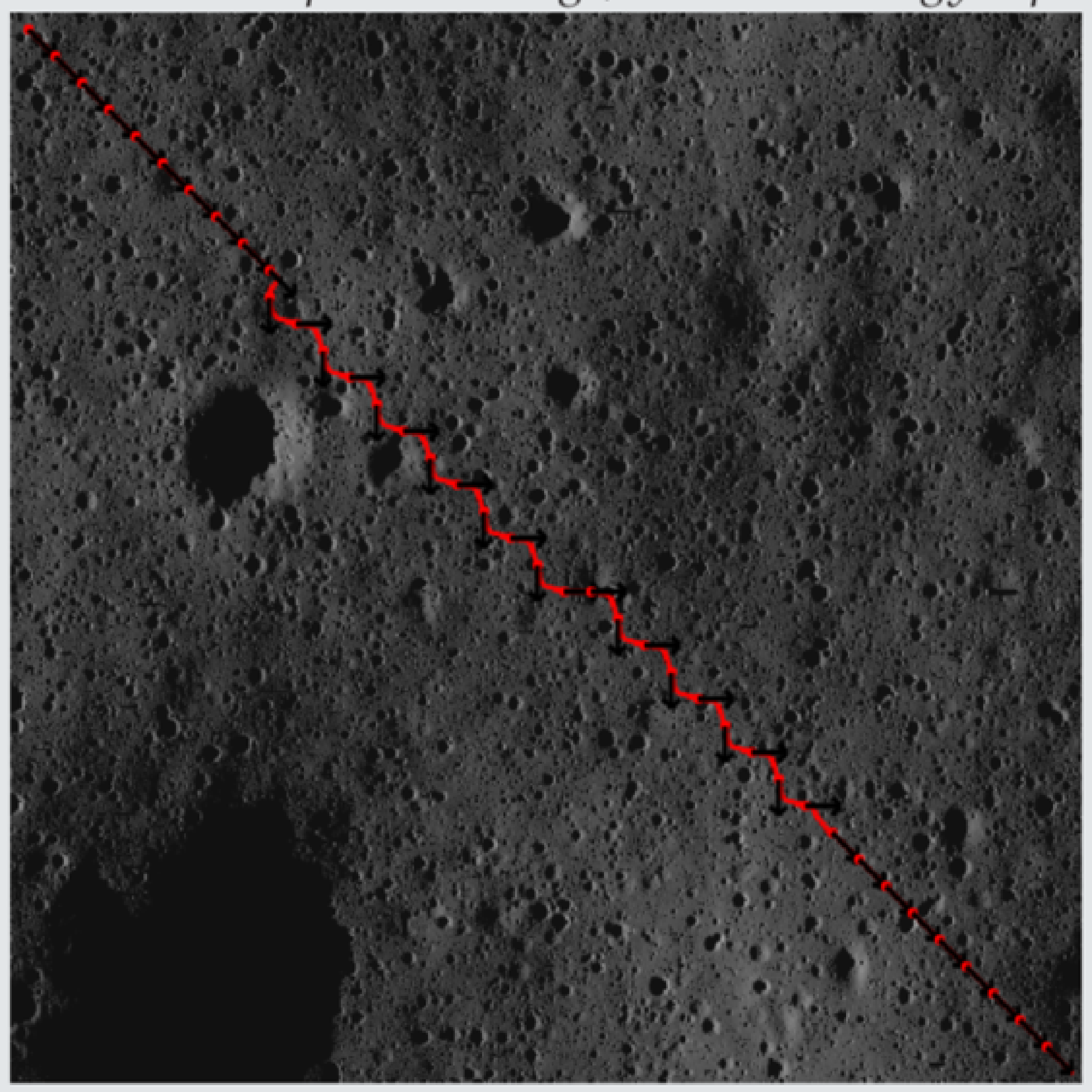
When sun angle is perpendicular to rover orientation, a zigzag path is optimal.

Constrain temperature range, minimize time



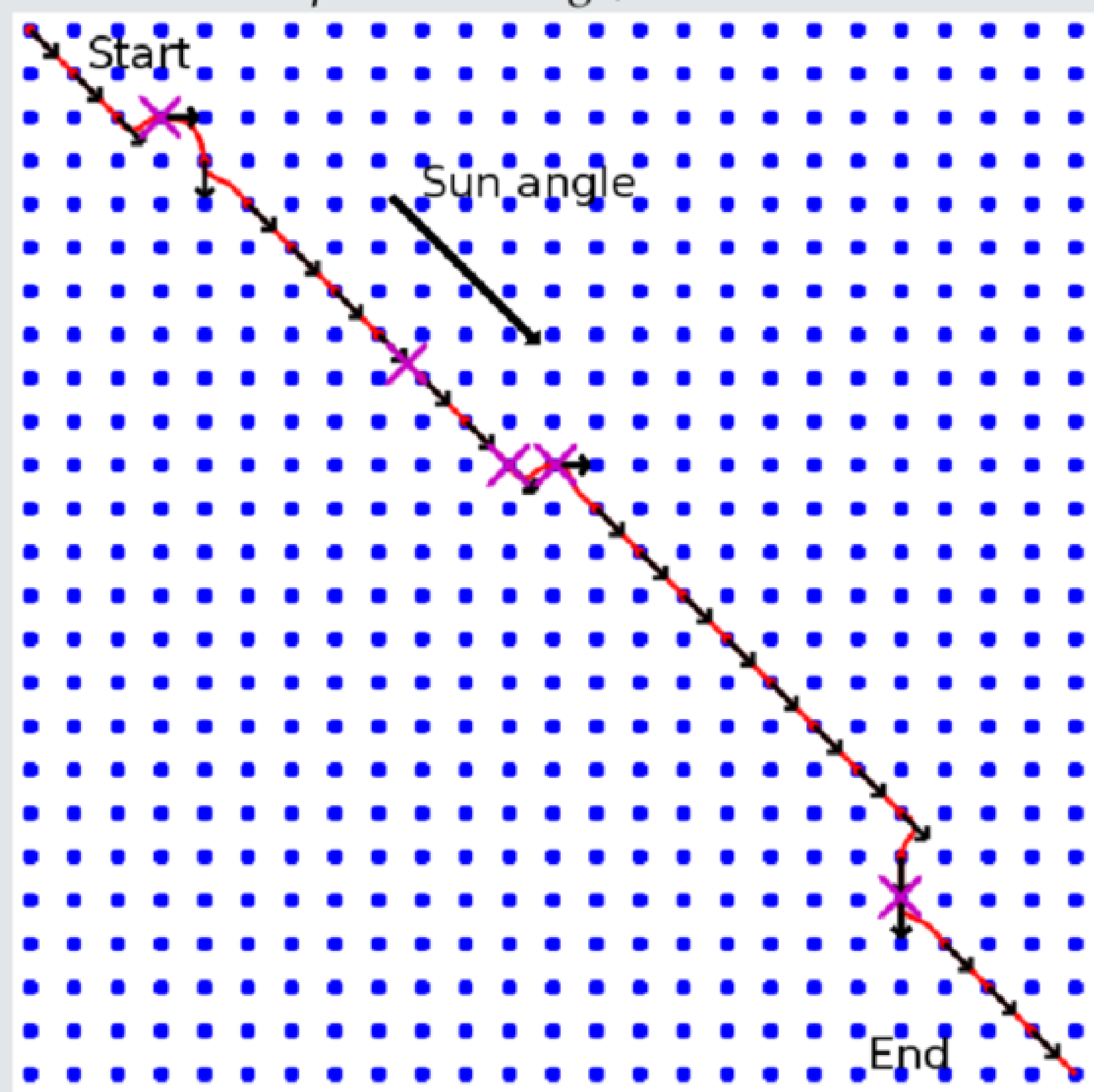
The rover turns its radiator away from the sun to cool down, then turns back to heat up again.

Constrain temperature range, minimize energy expended



The planner running on a map of lunar terrain at 10m/cell resolution.

Constrain temperature range, minimize distance traveled



The rover turns off its motors to decrease internal heat generation and reduce its temperature. The X's represent where the rover stops.

References

[1] P. Tompkins, A. Stentz, W. Whittaker. Automated Surface Mission Planning Considering Terrain, Shadows, Resources and Time In *i-SAIRAS '01*

Acknowledgments

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