Conference Poster

Impact of Traversability Uncertainty on Global Navigation Planning in Planetary Environments

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Impact of Traversability Uncertainty on Global Navigation Planning in Planetary Environments

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I. INTRODUCTION

Previous and current Mars rovers have relied on continuous human guidance to navigate safely on the red planet. As a result, traverse distances have typically been limited to less than 100 metres per sol; this distance has only very rarely been exceeded in a single drive. For example, prior to experiencing mechanical issues, the Opportunity rover performed a record drive of 219.89 metres on sol 410—this is the only time that a rover has driven more than 200 meters in a single sol [1]. On average, the Curiosity rover has moved 28.89 metres per drive and has driven once every 3.37 sols during the first seven years of its mission [2]. Although the focus of missions launched to date has been to investigate 'local' sites, enabling rovers to drive several hundreds of metres per sol could dramatically increase both the scale and pace of scientific discovery on Mars. Already, there is growing interest in missions with more ambitious navigation requirements [3], [4].

Beyond ensuring that rovers with long-range navigation capabilities are able to avoid nearby hazards, it will be as important to properly characterize the uncertainty associated with the global (or *strategic*) plans defined by the operations teams (to be followed by the rovers). Having the ability to quantify terrain traversability confidence at a strategic level would be a step towards safe online autonomous global trajectory planning. The quantification could also lead to better fault prediction and proactive recovery in the context of long-range planning with human operators in the loop.

This short abstract aims to illustrate the impact of uncertainty quantification on global navigation planning in planetary environments. We consider the variance of the cost (e.g., in terms of time or energy usage) of trajectories that a rover may potentially follow during point-to-point navigation. The intuition behind our methodology is that, on planetary surfaces, terrain regions with similar properties should lead to similar traverse performance. As such, the telemetry collected when driving in a specific location should provide insights about the traversability of other close or distant sites that have similar characteristics, as determined from orbital data, for example. We formalize global navigation planning as a graph search problem where edge similarity can be quantified based on the underlying terrain properties. Preliminary results from our experiments using maps of Jezero Crater are presented in Section III.

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II. APPROACH OVERVIEW

We represent the planetary surface environment as a directed graph $G = (V, E)$ where V is a set of spatially-distributed vertices and E is a set of edges; the cost of an edge is defined by the the estimated traverse time to travel between the two associated vertices. We make use of Gaussian process regression (GPR) to correlate the traverse velocities along specific edges to the corresponding rover and environment configurations. These velocity estimates are then used to compute the traverse times for every edge. This formulation is similar to the Gaussian Traveler Problem (GTP) [5] which, conceptually, is a modified version of the well-studied Canadian Traveller Problem that explicitly considers spatially-correlated disturbances contributing to the edge cost uncertainty in the planning graph. However, the solutions proposed in [5] do not explicitly consider the cost variance of edges. Furthermore, the effects of the environment on the agent are assumed to be well represented by a model that is a priori known. In our implementation, we instead correlate environmental observations directly with the performance of the agent (rover).

We formulate the objective function for our problem using a combination of the edge traverse velocity mean and variance, which in turn is employed to compute a traverse time. To do so, we modify the *Replan by Mean* (RM) scheme proposed in [5] by utilizing an adjustable mean-variance cost metric to evaluate the velocity of the rover along every edge $e \in E$. An edge is characterized by a series of features $\mathbf{x}_e$; in our case, these features include the terrain type and the rover's attitude (pitch and roll) on the terrain. The velocity along an edge is defined by

$$v(\mathbf{x}_e) = \mu(\mathbf{x}_e) + \lambda\sigma(\mathbf{x}_e). \tag{1}$$

In Equation 1, $\mu(\mathbf{x}_e)$ and $\sigma(\mathbf{x}_e)$ are the mean and standard deviation of the traverse velocity for edge e (obtained via GPR), respectively, and λ is a mission-dependent risk tolerance parameter. Informally, a negative λ will encourage risk aversion while a positive λ will encourage the exploration of edges with greater cost uncertainty. The combination of a specific λ, an edge length, and a velocity prediction provided by GPR allows for the calculation of the traverse time.

III. RESULTS

We tested our algorithm by simulating a kilometer-long drive up the delta formation in Jezero Crater. The planning graph was generated using orbital maps that included elevation and terrain type with a resolution of five metres per pixel. Every pixel was associated with a vertex and connected to its eight adjacent neighbours. The terrain types were provided by the SPOC classifier [6] and were grouped into three larger categories (namely: cohesive soil, bedrock, and loose soil). Regions with unknown terrain type, slope greater than 20 degrees, or untraversable geologic formations were excluded from the graph. For each terrain type, we defined a custom reference traverse velocity function. These functions varied smoothly based on the rover's tilt (pitch and roll) but had different maximum values. We used one Gaussian process (GP) to approximate the velocity function of each terrain type. All GPs were defined to be zero mean with two-dimensional covariance functions combining a squared-exponential kernel and a white noise kernel. Before running a simulation, the reference velocity functions were randomly sampled to provide 'prior knowledge' about the environment. Similar to [5], this initial sampling was executed by retrieving the true cost of 15 random edges in the planning graph. The same prior knowledge was used for all of the simulations described below. The original RM algorithm proposed in [5] updates the planning graph every time a new measurement is collected (when moving through the graph), a strategy that does not scale to large environments due to the high computational cost of this operation. Instead, we update the planning graph after 10 edges have been traversed to reduce the computational overhead.

Figure 1 shows the result of three different simulations with $\lambda = -1$, 0, and 1 between the same start and goal locations. The actual trajectories followed (solid lines) are overlaid on top of two blended orbital maps: slope magnitude, represented by the pixel intensity (steep slopes are brighter) and terrain type (cohesive soil is blue, bedrock is grey, and loose soil is red). For each simulation, we also show the outcome of one of the multiple planning iterations during the drive (dotted lines) and we illustrate how different λ values influence planning behaviors.

With $\lambda = -1$, the planner was consistently more conservative in the face of uncertainty (similar to the way in which Martian rovers have been driven so far). Early in the drive, as shown in Figure 1 by the red dotted path, the planner selected trajectories through loose soil, since this is the soil type that is traversable with the greatest confidence. However, after collecting sparse observations in bedrock terrain, follow-on planning iterations produced a trajectory that remained on bedrock and avoided loose soil as much as possible. This behaviour occurs because traverse speeds are generally higher on bedrock terrain. Alternatively, with $\lambda = 1$, the planner generates more exploratory behaviours and favours terrain configurations with a greater chance of yielding slower velocities than those predicted. This choice would generally be better suited for missions where the acquisition of data about unknown terrain configurations is deemed to be important. In Figure 1, the exploratory behaviour is demonstrated by the planner's choice to drive through steeper terrain initially, and then by its selection of shallower terrain after discovering that shallow terrain has higher traverse velocity. Finally, with $\lambda = 0$, the variance of the cost of every edge is ignored and only the expected traverse velocities are considered.

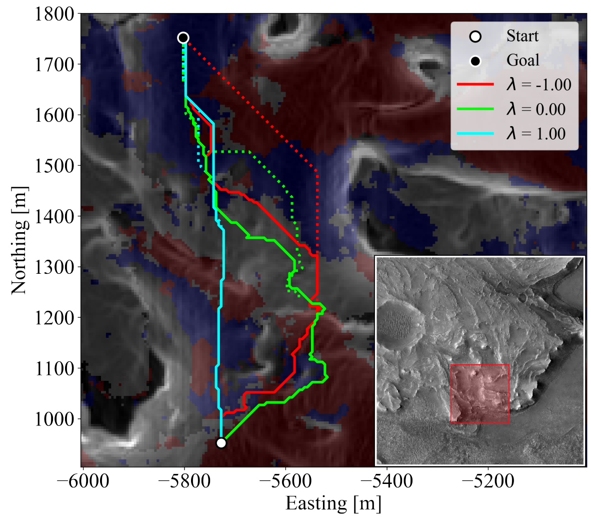

Fig. 1. Two georeferenced orbital maps of Jezero Crater blended together (slope magnitude, indicated by pixel brightness, and terrain type, indicated by pixel color). This terrain is located in the southern region of the delta formation. Three trajectories (solid lines) with different λ values are shown. For each simulation, the output of one of the numerous planning iterations during the drive is also shown (dotted lines). For $\lambda = -1$, 0 and 1, the actual traverse cost of each trajectory is 4802, 5755 and 3735 seconds, respectively.

IV. FUTURE DIRECTIONS

The preliminary work introduced herein aims to initiate a discussion about the impact of traversability uncertainty on global planetary navigation planning. Follow-up research will include the investigation of spatially non-uniform graphs (instead of using a high-resolution lattice over an orbital map), the fusion of different data sources to formulate more realistic traversability priors, and the use of non-static cost functions that vary over longer distances (simulating, e.g., degrading rover systems or changing terrain properties with time).

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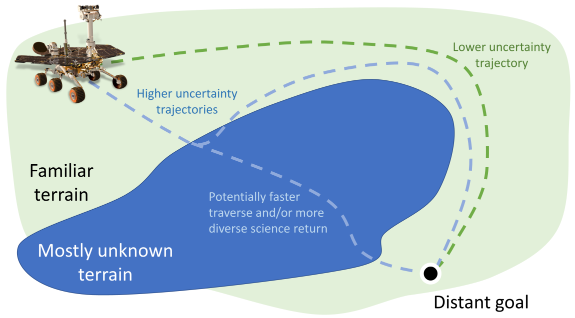
Introduction

Given the growing interest in planetary rover missions with ambitious navigation requirements, we illustrate how traversability uncertainty consideration can affect global (or "strategic") planning outcomes:



How could terrain traversability uncertainty estimation help?

- Adjust confidence levels to meet navigation constraints (activity scheduling, science return diversity and more).
- Adapt to an evolving rover-terrain interaction model over long distances (caused by changing terrain properties based on type locality and/or degrading rover subsystems).
- Assist human operators in improving the prediction of faults and quickly recovering from them.

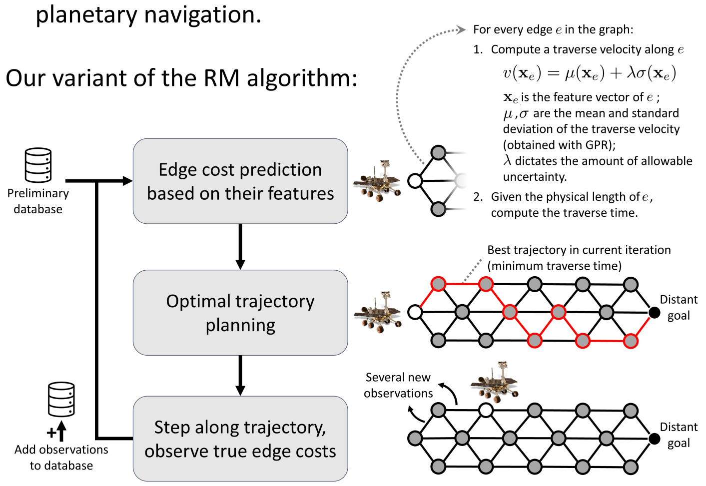
Algorithm inspiration: the GTP

Our work builds upon the Gaussian Traveler Problem (GTP) formulation, which seeks to iteratively minimize the expected traverse cost through a graph subject to uncertain environmental properties. It is a combination of a Canadian Traveler Problem and Gaussian Process Regression (GPR).

Our algorithm is based on the "Replan by Mean" (RM) scheme and differs from it in 2 ways:

- Explicit consideration of traverse cost prediction uncertainty across the planning graph.
- Testing on a large graph, which is common in global planetary navigation.

Our variant of the RM algorithm:

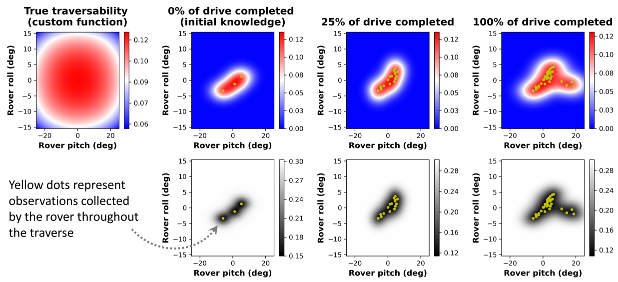


Preliminary Results

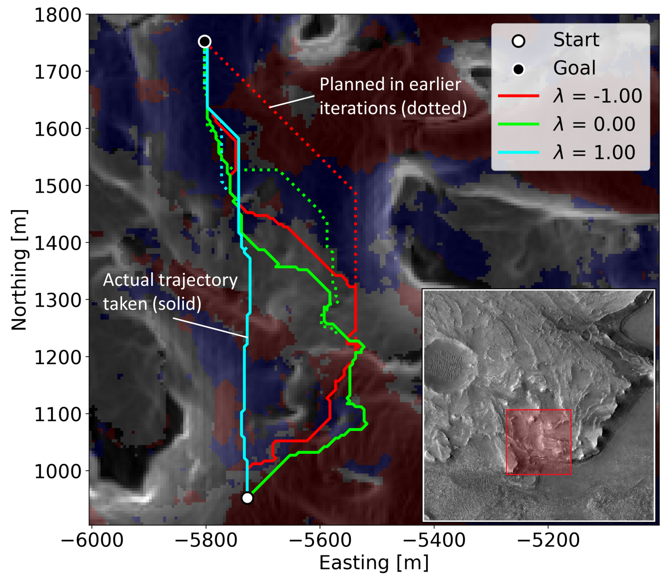
A customized smooth velocity function as a function of rover tilt (pitch and roll) was defined for three different terrain types. Gaussian noise was added during the simulated traverses.

Initially, the velocity function of each terrain type is sparsely sampled, constituting the rover's prior knowledge. New observations refined the rover's prediction and confidence about the traverse velocities on different terrain types.

For example, here is are the predicted velocity means (top row) and standard deviations (bottom row) in m/s obtained with GPR for a single terrain type during a simulated drive.



Experiments were conducted using orbital data of Jezero Crater. Map pixel brightness represents slope magnitude while pixel colors represent one of three terrain types. Every simulated drive started with the same initial traverse velocity knowledge but employed different λ values.



Future Work

- Smarter non-uniform spatial sampling over large spaces to reduce computational effort.
- Fusion of different data sources to formulate more realistic prior traversability knowledge.
- Utilization of an evolving cost function to simulate a changing rover-terrain interaction model.

Get in touch!

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